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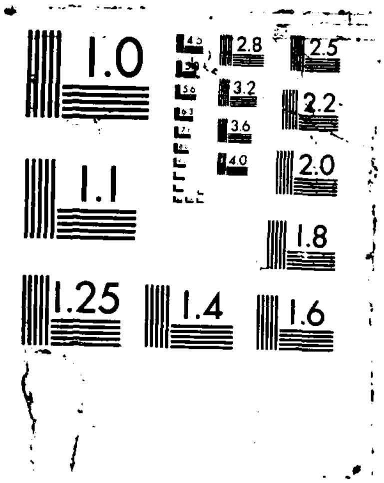
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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

DEFENSE CONTRACTOR'S COST ESTIMATING
METHODS FOR STATE-OF-THE-ART EXTENSIONS

by

Dale C. Rieck, Jr.

December 1987

Thesis Advisor: Willis R. Greer, Jr.

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The Navy's various weapons project officers routinely decide whether to use existing weapons technology or to extend into as yet undeveloped technology. For state-of-the-art (SOA) extensions, initial estimates of development cost frequently are inaccurate. This study first examines the background of methods utilized for SOA extension measurement. This study also reviews the cost estimating methods used by Litton Applied Technology, Inc. to estimate the development costs of the AN/ALR-67 Radar Warning Receiver, a specific SOA extension project. The principal findings are that regression analysis and geometric surface analysis are used to quantify SOA extensions, but only in theoretical applications. Litton Applied Technology uses the bottoms-up approach to estimate development costs. The future trends in defense cost estimating are also forecasted.

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Defense Contractor's Cost Estimating Methods for States-of-the-Art Extensions

by

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ABSTRACT

The Navy's various weapons project officers routinely decide whether to use existing weapons technology or to extend into as yet undeveloped technology. For state-of-the-art (SOA) extensions, initial estimates of development cost frequently are inaccurate. This study first examines the background of methods utilized for SOA extension measurement. This study also reviews the cost estimating methods used by Litton Applied Technology, Inc. to estimate the development costs of the AN/ALR-67 Radar Warning Receiver, a specific SOA extension project. The principal findings are that regression analysis and geometric surface analysis are used to quantify SOA extensions, but only in theoretical applications. Litton Applied Technology uses the bottoms-up approach to estimate development costs. The future trends in defense cost estimating are also forecasted.

TABLE OF CONTENTS

I. INTRODUCTION

A. PURPOSE

This thesis will describe how Litton Applied Technology of San Jose, California measured and estimated the cost of the state-of-the-art development of the AN/ALR-67 Radar Warning System. This case study will be utilized by Professor Willis Greer to test an improved cost estimating model which will relate measurements of state-of-the-art extensions with costs.

B. BACKGROUND

During the past three years, budget restraints have forced the Navy to tighten controls over expenditures for major weapons systems. One area which has generated significant unplanned cost growth during the last two decades has been the extension of states-of-the-art (SOA). The cost impact of SOA extensions is most keenly felt during the demonstration and validation phase, and the full scale development phase of the acquisition process. During an interview with GTE cost analyst Stan Swales on 17 September 1987, he estimated most cost models for initial SOA development efforts were only accurate to within twenty to forty percent. However, once the generic cost models were "calibrated" with actual cost parameters and the technical characteristics of the completed system, the range of accuracy could be reduced to five to ten percent. [Ref. 1]

During the concept exploration process of new weapons systems, the Navy must decide if the risks of unplanned cost growth should deter extending as-yet undeveloped technology. Prior contractor research, primarily by the Rand and General Research

Corporations, has made progress in defining and measuring the extent of technological change in complex defense systems, primarily aircraft related. These prior studies have concentrated on the generation of cost models for specific applications under Department of Defense (DOD) contracts, rather than a defined cost model for general use by Navy systems commands. For example, Dr. E.N. Dodson developed the High-Energy Laser Systems Cost Model (Caliper II) for the Air Force Weapons Laboratory at Kirkland Air Force Base, New Mexico. [Ref. 2] However, the Navy has yet to coordinate new cost estimating models with the Air Force.

Cost models which could accurately delineate the association between levels of SOA extensions and cost overruns would enhance budgeting accuracy. Most budget analysts for multimillion dollar weapons systems utilize the Work Breakdown Structure (WBS) authorized by the DOD Cost/Schedule Control Systems Criteria. [Ref. 3] Effective, comprehensive cost models are required for initial hardware development cost estimates, particularly in the constantly changing electronics environment. The Navy's negotiating capabilities during acquisition for new technological systems will be strengthened with increased expertise in SOA extension resource estimation.

One field rapidly gaining in importance and magnitude is software cost estimating, which experts like Elmer Branyan from General Electric predict will account for eighty-five percent of all embedded computer costs by 1990. [Ref. 4] Defense cost models must assimilate and utilize the latest techniques incorporated in software models developed by RCA

(Price-S model) and Hughes Aircraft (developed by Dr. Jensen).

Hardware cost estimation for initial developed relies on three primary tools: estimation by analogy, use of cost estimating relationships (parametric costing), and systems engineered analysis (detailed bottoms up estimation). These three methods are applied on the basis of available data, which will be differentiated and described in Chapter Two.

The following quotation by Larry Smith emphasizes the fundamental nature of accurate estimating:

> The process of estimating is the process of making a prediction or forecast of predefined events and/or occurrences weighted and influenced by subjective and objective information. The planning techniques that are available rely on the estimates to develop schedules, resource histograms, budgets, cash flow histograms, and performance standards. The results and sophisticated methodology are only as good as the input estimates. The time spent developing good estimates and the understanding required to produce good estimates, will reduce the need for major revisions to the plan and schedule. Good estimates will reduce schedule slippage and cost overruns and set the stage to facilitate the implementation of project plans. [Ref. 5]

C. OBJECTIVE

The objective of this thesis is to describe and analyze how defense contractors control the cost of states-of-the-art extensions. Litton Applied Technology, located in San Jose, California will be the subject of the case study. This thesis compares Litton's development cost estimate of the AN/ALR-67 Radar Warning System with their actual development costs. Also, Litton's methodology for quantifying the SOA extension to the AN/ALR-67 Radar Warning System is analyzed.

The following factors integral to Litton's management of the AN/ALR-67 Radar Warning System are also discussed:

1. Litton's cost estimation process for each of the following acquisition phases: concept exploration demonstration and validation, full-scale development, and initial production. The process description will indicate which cost techniques were utilized by Litton for each phase.
2. Litton's use of modern parametric models in hardware and software cost estimation.
3. Soundness and range of Litton's control system in monitoring and reducing cost, schedule, and performance variances.
4. Specific variance analysis by phase, concentrating on the effectiveness of Litton's cost model.
5. External factors impacting Litton's current initial production, such as the current GAO investigation of commonality problems between Navy and Air Force radar warning receivers.
6. Organizational design and interaction of the primary departments involved in the SOA extension.

A key secondary objective, as discussed in Chapter Two, is to clearly delineate the history of previous research of states-of-the-art extension questions. The fundamental theory and key elements of early SOA measurement equations from 1965 to 1985 are outlined. Examples of SOA model applications to aircraft turbine engines, ground combat surveillance radars, computers, and laser weapons systems is presented.

D. THE RESEARCH QUESTION

The primary research question examined was: how effectively did Litton estimate the development and production costs of the state-of-the-art extension of the AN/ALR-67 Radar Warning System? Subsidiary questions will deal with Litton's budgetary models for predicting and controlling costs. Their methods of cost control are also explored.

Three subsidiary questions were:

1. What previous research has been conducted on weapon system's state-of-the-art extensions?
2. Which cost estimating relationships were utilized in Litton's cost estimation of the development program?
3. Was there an association between levels of SOA extension and cost overruns?

E. SCOPE AND LIMITATIONS

This thesis concentrates on two specific areas. First, Litton's cost estimation process in measuring the state-of-the-art advance from the AN/ALR-45 to the AN/ALR-67 Radar Warning System is thoroughly discussed. Second, the SOA measurement theory, control and planning techniques for defense contractors involved in research and development programs is analyzed. For example, the general nature of the S-curve is described. The S-curve represents how technology initially advances slowly, then rapidly gains momentum and eventually slows down when it nears the natural limits of the technology. [Ref. 6] Contractors must be able to accurately locate their exact position along the curve, to determine applicability of SOA extensions.

In summary, the case study describes, then assesses Litton's ability to accurately predict and control development and production costs for the AN/ALR-67 Radar Warning System. Peripheral information is provided as review factors in the organization and budget process which contribute to the firm's success.

The principal limitation of this case study is that there is no guarantee that observations are transferable to another environment, setting, project, or firm. For example, the unique mission of fighter aircraft radar warning systems may negate the transfer ability of finds to commercial aircraft manufacturing firms. Also, one sample may not be truly representative of shipbuilding projects, the primary focus of Litton's other defense divisions.

Litton Applied Technology placed restrictions on availability of the exact algorithms utilized in their cost-estimation model. Specific cost data which might reveal overhead rates or management reserve factors to their competitors was withheld. Also, the cost estimator primarily responsible for initial development costs during the 1975-79 time frame was not available for interviews. The rationale behind the initial cost estimates was not clearly documented, so many observations of the SOA extension will be based on secondary sources. Additionally, due to the unclassified nature of this thesis, many current mission and performance parameters of the AN/ALR-67 Radar Warning System are omitted.

F. LITERATURE REVIEW AND METHODOLOGY

Extensive research has been conducted on methods of cost estimation for weapons systems. The majority of the literature is based on parametric models, both for hardware and software cost estimation. Significantly less literature, however, is available on measurement of state-of-the-art advances. Knowledge about the critical process of high technology cost estimation will enable a more credible analysis of Litton's cost estimation procedures for the AN/ALR-67 Radar Warning System. This case study can then explore the extent to which theoretical research from the past two decades is practically utilized, if at all, by one of our country's leading defense electronics manufacturers.

For SOA extensions background literature, the following key authors and their specialties are highlighted:

1. A.A. Alexander: estimation of advanced technology in turbine engines.
2. E.N. Dodson: quantitative measurement of state-of-the-art through use of planar and ellipsoid surfaces.
3. Richard Foster: analysis of the S-curve, or Gompertz curve, characteristics.
4. Results from the 1983 Technological Forecasting Conference which focused on this area.

The methodology for this thesis primarily was a case study of Litton Applied Technology, Inc., in San Jose, California. Specifically, personal interviews were conducted over a period of two months with the top managers involved in the AN/ALR-67 development. Among the key company personnel interviewed were Eugene E. Deimling, Director of Business Development, and Donald R. Bowden, Director of Cost Estimating and Analysis. Personal interviews were also conducted with Dr. Edward Dodson, Director, Economic Resources and Planning Group of General Research Corporation, Santa Barbara, California, and Stan Swales, Cost Estimator for GTE Government Systems, Inc., Mountain View, California.

Searches through the Naval Postgraduate School Library and the Defense Logistics Systems Logistics Exchange were also conducted. The primary journals investigated were "Research Management", "IEEE Transactions on Engineering Management", and "Technological Forecasting and Social Change". Also, current articles ordered from the librarian of the Space Systems Cost Analysts Group and the International Society of Parametric Analysts, Mr. Clyde Perry, were reviewed.

Finally, the Litton Pricing and Cost Estimation Manual was examined, with particular emphasis on procedures for state-of-the-art developments.

G. ORGANIZATION OF STUDY

The remaining chapters of this thesis are organized as follows:

1. Chapter Two: Literature review of previous studies of state-of-the-extensions measurement theory is presented. Also, comparisons between various hardware and software cost estimating models are made. Mechanisms espoused in current literature for controlling high technology development projects is briefly outlined.
2. Chapter Three: A historical narrative of two cost estimation models by Dr. E.N. Dodson is presented. Examples will depict cost elements which have factored into them SOA technological factors.
3. Chapter Four: The actual cost data from the AN/ALR-67 is presented, along with a description of Litton's pricing and cost estimation system. Interviews with key individuals are addressed.
4. Chapter Five: The analysis of variances found in the cost data, and external events which have impacted Litton's development of the AN/ALR-67

are discussed. Comparisons from the case study to relevant theory are made.

5. Chapter Six: Conclusions and recommendations developed in this case study are concisely stated. Areas for future research are identified.

II. LITERATURE REVIEW

A. INTRODUCTION

This chapter explores the background literature pertinent to measurement and control of state-of-the-art advances. In particular, a chronological outline of SOA measurement history from 1969 to 1985 is presented. The chapter is subdivided into the following key areas:

1. Ostwald's basic guidelines for measuring technological advances and cost estimating relationships.
2. Dodson's approach to quantitative measurement of advances in state-of-the-art in January 1969.
3. Dodson's studies in resource estimation for development programs from October 1969.
4. Rand Corporation's study of measurement of technological change in aircraft turbine engines (June 1972).
5. Hovanssian's description of key parameters integral to research and development of large-scale electronic systems (August 1975).
6. Dodson's development of cost equations to measure technological change in high-technology systems (May 1977).
7. Gordon and Munson's proposed convention for measuring the state-of-the-art of products (1981).
8. Alexander and Mitchell's measurement of technological change of heterogeneous products (1985).

9. Martino's measurement of technology using tradeoff surfaces (1985).
10. Dodson's measurement of SOA and technological advance (1985).
11. Cooley, Hehmeyer, and Sweeney's model of research and development resource allocations (1986).
12. McDonough's identification of effective characteristics of management control systems of new product development projects (1984).
13. Smith's summarization of best techniques for estimating time, cost, and resources in new developments (1985).
14. Evaluation of the key hardware and software cost estimation models used in advanced technology development and production contracts.

B. OSTWALD'S BASIC TOOLS FOR COST ESTIMATING

Ostwald's "Cost Estimating for Engineering and Management", published in 1974, provides the essential basis for detailed, practical cost estimates. [Ref. 7] Stan Swales, cost estimator at GTE, recommended Ostwald's book as a prerequisite to analyses of current cost estimating techniques. Ostwald details the first unified treatment of the philosophy, concepts, and practices of the cost estimating field. The fundamentals of three ideas pertinent to later studies of SOA advance are introduced: cost estimating relationships (CER's), cost indices, and technological forecasting.

1. Cost Estimating Relationships

Ostwald describes CER's as functional models that mathematically describe the costs of components as functions of one or more independent variables. CER's are used to estimate physical quantities such as number of radars or personnel. CER's also can express rates of activity for support personnel as a function of the number of direct radar operators, for life cycle cost studies. In aerospace electronic industries, CER's can be used to estimate turbojet engine development cost as a function of maximum thrust and production quantity. Three fundamental elements must be present in CER's:

a. Logical relationship of the variable to cost,
b. Statistical significance of the variables' contribution, and
c. Independence of variables to the cost explanation.

2. Technological Forecasting

Ostwald defines technological forecasting as "logical analyses that leads to quantitative conclusions about future engineering qualities and properties." [Ref. 8] He recommends evaluation of technology trends to find the critical independent variables on which the dependent variables rely. Correct analysis of the S curve is an essential ingredient. The S curve is a feature of nature that diagrams how electronic components are subject to flat and slow growth in the early years, rapid middle-life development, followed by stability and eventually decline as new products evolve. General technical history books provide back-up documentation.

3. Cost Indices

Ostwald also describes how cost indices enable estimators to forecast the cost of new designs based on similar items in the past, without going through detailed "bottoms-up" costing. The cost index is a dimensionless number for a given year, indicating the cost of that year relative to a base year. The shows the conversion from costs to equivalent costs in the present.

C. DODSON'S APPROACH TO QUANTITATIVE MEASUREMENT OF ADVANCES IN STATE-OF-THE-ART (JANUARY 1969)

In 1969, Dr. E.N. Dodson defined state-of-the-art in concept as the highest degree of technical accomplishment that could be achieved at any point in time. [Ref. 9] This was later revised to represent the state of best implemented technology. This early study focused on parameters which comprehensively influenced achievable engineering designs.

Dr. Dodson stated that the following constraints must be met before SOA advances could be quantitatively measured:

1. A geometrical surface with continuous derivatives that interpolates between implemented design characteristics is used to approximate the true state-of-the-art.
2. The surface should be either convex or concave in all dimensions, permitting plane surfaces.
3. Each pair of design characteristics must be negatively correlated to allow tradeoffs on single state-of-the-art surfaces.

Considering these constraints, Dr. Dodson asserted that a convex hypersurface reasonably represented SOA surfaces. Actual data points are fitted to convex surfaces in ellipsoid geometric forms via mathematical relationships. The chosen physical or performance characteristics must be among those derived early in the concept exploration acquisition stage. These characteristics should be influenced by engineering development decisions to have relevance to SOA determination. Also, Dr. Dodson stipulated that characteristics should be specified so that increasing values corresponded with increasing technical difficulty.

Dr. Dodson worked with subsystems of solid propellant missiles, maintaining the Department of Defense Work Breakdown Structure. Three parameters of propulsion subsystems which met his mandatory prerequisites were: delivered specific impulse, propellant mass fraction, and length-to-diameter ratio. These parameters were considered the primary, but not all inclusive, factors which represented the technological advance. These variables influenced areas of SOA relevance such as variations in chamber pressure and burning rate. Dr. Dodson then assigned values to these parameters based on the Chemical Propulsion Information Agency Rocket Motor Manual. His next action was to classify these motors in various time periods according to year of development completion.

Dr. Dodson's purpose in quantifying measurements of advances in the SOA was to test the hypothesis that SOA extensions influenced the costs required for development programs. Through geometric methods, he based SOA measurement advances upon how data points fit above existing SOA surfaces. The data points represented the chosen parameters, classified by year of development. The measured SOA advance becomes a function of the proportionate increase in the radial drawn from the origin through the surface to the new data point. The SOA advance is indicated by the squared proportional increase.

Dr. Dodson summed up his 1969 study by stating that the measured SOA advance is comprised of these two factors:

1. Attributes of design efforts directly related to the particular system development program, and
2. Contributions from general research and development factors, which can be represented by dummy variables identified for specified major technological advances.

D. DODSON'S STUDY OF RESOURCE ESTIMATION IN DEVELOPMENT PROJECTS

Dr. Dodson, in a study for the Assistant Secretary of Defense, elaborated his earlier study on SOA advance. He described the SOA for a particular point in time, with n representing the number of SOA design characteristics. These characteristics could trade off upon one another. Some examples are weight, speed, and size for fighter aircraft's SOA.

Dr. Dodson indicated that Work Breakdown Structures should be used to divide whole weapons systems, such as missiles, into subsystems. SOA specification for an aggregate system would not be reliable since subsystem technologies are distinct and will advance independently of one another. For example, missile propulsion and guidance subsystems evolved separately, with different primary parameters. He recognized that information about performance, development costs, and development time of subsystem is severely limited, due to contractor reluctance to divulge this information.

In this report, Dr. Dodson concentrated on specifying SOA measurement equations for inertial guidance systems for missiles. Accuracy, weight, and reliability were selected as the principal parameters affecting SOA. These three factors could be quantified. They explained, based on engineering judgment, most of the resources spent on advancing the SOA.

The measure of SOA for accuracy was maximum range divided by Circular Error Probable (CEP) for inertial guidance systems. CEP represented the acceptable distance a missile must steer to its target. This distance could be fractions of miles for a nuclear-armed ballistic missile. Since state-of-the-art advance always increases, the above equation indicated that, as range increased, given accuracy became more difficult to achieve.

The measure of SOA for weight was the number one divided by the guidance system weight. Dr. Dodson's study found light guidance systems outperformed heavy ones since they permitted greater range and payload.

The SOA parameter for reliability was mean-time-between-failure (MTBF). For inertial guidance systems, reliability was critical due to the continuous state of twenty-four hours a day alert status.

Dr. Dodson indicated several reasons why production cost was not a good choice for an SOA parameter:

1. Costs prior to development would be derived from cost estimating relationships, which would not be historically reliable.
2. Learning curves could not be established before actual engineering efforts had been expanded to reduce costs.

Finally, by geometric measures of the data points for accuracy, weight, and reliability on an ellipsoid surface, SOA advance indices were developed. Some SOA index numbers were 2.945 for the Pershing missile, and 120.200 for the Polaris missile. Research using the SOA parameters demonstrated Pershing had a relatively low SOA advance for two reasons:

1. Relatively low accuracy at maximum range, and
2. Low reliability.

Finally, Dr. Dodson devised a logarithmic approach to measure the cost of an SOA advance, in relation to time. His basic hypothesis stated that time and cost are interrelated resources. He developed an equation treating the cumulative cost to complete development (C) as a dependent variable, with the measured advance in SOA (S) as an independent variable. The elapsed time to development completion (T) would be stipulated by the planner. The equation took the form of:

$$\log C = a + b \log S + C \log T,$$

where a,b, and c were designated parameters, based on the system.

The next section outlines how Rand Corporation expanded on Dr. Dodson's approach.

E. MEASURING TECHNOLOGICAL CHANGE IN AIRCRAFT TURBINE ENGINES

Alexander and Nelson from Rand Corporation developed techniques in 1972 to measure technological advance in weapons acquisition. [Ref. 10] Their initial studies focused on aircraft turbine engines. Their goal was to capture mainstream trends and improve estimates of costs and schedules during the system acquisition cycle.

Alexander and Nelson used multiple regression analysis to develop an equation containing the primary parameters important in turbine engine technological change. Like Dodson previously, they estimated multidimensional tradeoff surfaces of the key turbine engine parameters. Using regression analysis, they traced out the movement of the tradeoff surface over time.

The equation they developed to calculate indices for turbine engine development was:

$$\text{Tech} = -1187.5 + 156 \text{ Ln Temp} + 18.8 \text{ Ln Thrust} - 26.5 \text{ Ln Weight} - 20.6 \text{ Ln SFC} + 11.7 \text{ Ln Q} + 13.0 \text{ Prop}.$$

The dependent variable represented the technology index, which was measured in quarters of a year beginning in January 1943. The independent variables represented were:

1. Temp = turbine inlet temperature in degrees Rankine.
2. Thrust = military sea level static thrust in pounds.
3. Weight = engine weight in pounds.
4. SFC = specific fuel consumption at military sea level staticthrust (lb/hr/lb).
5. Q = maximum dynamic pressure in pounds per square foot.
6. Prop = dummy variable, equal to one if the engine was a turboshaft or turboprop, zero or otherwise.

Alexander and Nelson found that the major turbine engine manufacturers had similar tradeoff surface shapes. However, the two major manufacturers, General Electric and Pratt and Whitney, were approximately two years ahead of their competitors in level of technology.

Alexander and Nelson specifically addressed the question: "Can a technique be developed for objectively quantifying the technological state of the art of a particular type of system?" [Ref. 11] Their analysis utilized the following two assumptions:

1. Limited numbers of parameters adequately characterized the system under study.

2. Historical continuity prevailed such that the selected parameters characterized the system even during different time periods.

Alexander and Nelson also recommended the use of performance parameters rather than technical parameters, to give greater emphasis to outputs than inputs. However, they acknowledged their final equation contained both technical and performance parameters. Their data used in their study came from engine manufacturers, and standard sources such as "Jane's All the World's Aircraft." Turbine engines were well-suited for analysis due to their strong technological trends, such as the increase in aircraft speeds and the progression of engine types.

Alexander and Nelson subjected the data to statistical tests with different subdivisions to find the equation with the best "fit" over the tradeoff surface. However, they did not develop specific equations for obtaining the cost of development of the technological advance. They hypothesized quantification of the technological setting were necessary prerequisites, before the cost question could be answered.

In the next section, Hovassian's Key Parameters necessary for development of electronic systems are examined.

F. HOVANSSIAN'S DESCRIPTION OF KEY PARAMETERS

Hovanssian described the research and development phase of a hypothetical large-scale electronic system, based on his study of applicable programs. [Ref. 12] He stated that the initial design phase should always include a state-of-the-art analysis of the key system design parameters. This analysis should include a risk evaluation of potential problem areas such as technology, cost, or time. He stated that the more current performance measures are advanced, the greater the risk involved.

Hovanssian did not develop any models to estimate the SOA advance. However, many of his cost estimating techniques matched those of Litton Applied Technology. Litton's cost model is described in Chapter Four.

Hovanssian stated that the cost-estimating relationship technique should only be used during early stages of development. He recommended that the cost-estimating relationships be based on statistical analysis of similar equipment. If statistical data on similar equipment was not available, then he recommended the utilization of "bottoms-up" system-level cost estimating. In systems-level estimating, costs are derived from consideration of manpower, basic units, components, parts, or other relevant factors.

Hovanssian also described "design-to-cost" modeling. In this technique, various design configurations are tested against specified performance parameters. The successful design configurations are traded off to determine which yields the lowest life-cycle cost. Life-cycle costs included both the total procurement cost of the system and its future operating costs.

Finally, Hovanssian stated that most electronic systems must include customer-acceptance parameters at the development stage, or face possible cost overruns later in the life-cycle. Among the parameters listed were:

1. Life cycle cost.
2. Maintenance skill required to repair the system.

3. Number of maintenance employees required to keep the system in working order.
4. Percentage of time the system is available for use.
5. Reliability (measure elapsed time between two consecutive failures).
6. Amount of maintenance required per operating hour.
7. Quantity and type of spare parts required.
8. Operator approval of new system.
9. Degree of automation.
10. Improvement over previous systems.

In summary, Hovanssian's paper pointed out many parameters and fundamental concepts which entered into the design and development process for large electronic systems. In the next section, Dr. Dodson's updated 1977 study on quantification of SOA advance is outlined.

G. DODSON'S DEVELOPMENT OF COST EQUATIONS TO MEASURE TECHNOLOGICAL CHANGE

In May 1977, Dr. Dodson outlined procedures to account for technological change via research and development cost equations. He indicated research and development costs were directly influenced by the degree of extension to the SOA by a given program. [Ref. 13] His measurement approach to the SOA advance evolved from a combination of his earlier study (discussed in section C) and Alexander and Nelson's paper (discussed in section D). Dr. Dodson felt this new approach would be easier to implement.

This approach featured four key elements:

1. Independent variables for a multiple regression

equation would consist of a limited number of key technical parameters.

2. The dependent variable would be a consistently defined calendar milestone. For example, a completion of qualification test would represent this milestone for applicable subsystems.
3. An expected date (Ye) for achievement, for the parameters designated as independent variables, would be the result of a multiple regression exercise.
4. The residuals of the difference between the expected end the actual date of achievement (Y estimated - Y actual), would be the measure of the relative technological advance.

Dr. Dodson illustrated his theory through his previous research on avionics computers. The computers' key parameters were selected from technical data as:

1. The speed of the computer in operations per second.
2. The density of the central processing unit in pounds per cubic foot.
3. The number of distinct instruction types in the computer.

Dr. Dodson also documented the actual date of development completion for each computer as Y actual. The difference between the expected and actual dates of completion represented the change in SOA, in units of years.

Once the residual was calculated, it was incorporated into a cost estimating relationship. The dependent variable would represent the development cost associated with the specific SOA advance. The independent variables were:

1. X1, which represented the residual difference between the expected and actual dates of development completion.
2. X2, which equalled one for microprogrammable computers, or zero for synchronous computers.
3. X3, which equalled one for space computers, or zero for airborne computers.

The resulting equation developed by Dr. Dodson to calculate the monetary amount correlated with SOA advance was:

$$Y = 6.11 + 2.7\ X1 - 4.57\ X2 + 14.8\ X3$$

Dr. Dodson recognized several limitations to his SOA measurement approach. The equation might simply reflect a change of mission requirements, rather than indicate technological advance. To remedy this potential problem, he recommended that variables should be stated via efficiency measures like thrust per pound, rather than absolute-scale measures like thrust.

Dr. Dodson also recommended in this paper that electronics development firms should develop an output index to account for year-to-year changes in manufacturing productivity. He felt that failure to consider productivity changes contributed to errors in estimating electronics procurement costs. Two reasons for productivity changes were:

1. Changes in design and manufacturing technology which reduce the cost per unit of output.
2. Operational requirements for performance increases.

Using costs as the dependent variable, cost estimating relationships were derived by Dr. Dodson for the technology output indices. In this case, the year of development completion became an independent variable. The regression coefficient represented the annual change in costs due to shifts in the relationship between productivity and cost.

In summary, Dr. Dodson developed a method to measure the financial impact of SOA advance. In the next section, Gordon and Munson proposed an alternate method for measuring the SOA advance.

H. GORDON AND MUNSON'S PROPOSED CONVENTION FOR MEASURING THE SOA OF PRODUCTS

In 1981, Gordon and Munson developed for the National Science Foundation a general equation to measure SOA advance. [Ref. 14] The equation derived was:

$$SOA = K1\ (P1/P2') + K2\ (P2/P2') + \ldots\ Kn\ (Pn/Pn').$$

In the above equation Kn represented the relative weight associated with each parameter describing the technology. Pn indicated the value of the parameter chosen to describe the SOA, while Pn' represented the maximum reference value of the parameter.

Gordon and Munson developed their SOA equation to satisfy the following criteria:

1. The same estimate of SOA should be produced by any analyst studying the same technology.
2. The SOA value should be in an index format, based on a reference value.
3. The equation should satisfy any level of technological aggregation.

Gordon and Munson discussed two techniques critical to the choice of parameters and their relative weights: Judgmental and statistical techniques. They recommended Delphi-related procedures, the utilization of experts to choose the proper parameters for the SOA equation. Delphi procedures sought expert judgment via anonymity and controlled feedback, to obtain the most objective inputs. For example, electronic voting devices were utilized to allow expert practitioners freedom to provide anonymous answers to questions posed by group moderators.

Gordon and Munson also listed several statistical methods available to estimate weights and parameters of the SOA equation. The techniques included: multiple regression, stepwise regression, discriminate analysis, cluster analysis, multidimensional scaling, and factor analysis. In factor analysis, for example, a correlation matrix was utilized to group variables into classes of highly correlated components. These classes were taken as parameters through construction of an index from individual members of the class.

Gordon and Munson applied their theory against antibiotics and computers. They formulated a performance index for computers based on the judgments of an expert panel using the Delphi approach. The following three parameters were chosen to characterize computers:

1. Computer speed by operations per second.
2. Cost of computation by operations per dollar.
3. Maximum memory size by kilobytes.

Gordon and Munson used computerized statistical techniques, based on their assumption that the state-of-the-art function is an S-shaped curve. Using their results, they developed an SOA index for computers, ranking the IBM 3033 computer as the SOA leader.

Gordon and Munson felt their process of calculating SOA measures could be applicable to any field, including integrated circuits. In the next section, Alexander and Mitchell's study of technological change of heterogeneous products is outlined.

I. ALEXANDER AND MITCHELL'S MEASUREMENT OF TECHNOLOGICAL CHANGE

In 1985, Alexander and Mitchell developed procedures to measure technological change of heterogeneous products. [Ref. 15] They designed a framework in which to place empirical measures of technological change, hedonic price indices, and cost estimating relationships. In this study they estimated technological change equations for milling machines, turbine-powered airliners, and turbine engines. Like Dodson earlier, they realized product characteristics alone could not define technological change.

Alexander and Mitchell derived a tradeoff function, based on a tradeoff surface of cost, performance, technical characteristics and time. The entire tradeoff surface represented the state-of-the-art of a given period. The tradeoff function was written as:

$$C = C(P1, \ldots, Ps, q1, \ldots, qj. t).$$

The variables in this function were:

1. "C" = average cost of the product.
2. "P" = performance characteristics or user outputs.
3. "q" = factor prices (assumed to be fixed).
4. "t" = time.

Their equation meant technological change in products arose from three factors:

1. Productivity or performance improvements.
2. Improved factor inputs.
3. Production process improvements.

Alexander and Mitchell noted that their equation took the form of the typical cost estimating relationship, with cost as the dependent variable. The dimensionality of the state-of-the-art surface was limited by the difference between the total number of variables and the number of constraints. Their most important reason for including costs in the measure of technological change was their belief that higher levels of performance were attained through the expenditure of more resources.

Alexander and Mitchell studied the technological histories of milling machines, airframes, and aircraft turbine engines, summarizing their specific results in this paper. They concluded that measures based on product characteristics must be evaluated carefully, since selection of a few core characteristics often neglects other attributes whose relative importance my have changed over time. They felt productivity measures based on user outputs, such as cost per mile for aircraft, were more likely to capture the totality of technological change.

In the next section, Martino's studies, which also concentrated on measurement of SOA surfaces, are highlighted.

J. MARTINO'S MEASUREMENT OF TECHNOLOGY USING TRADEOFF SURFACES

In 1985, Joseph Martino followed up Alexander's theoretical derivation of the designer's tradeoff surface with an empirical approach. He concentrated only on those technical parameters which were relevant to measuring the SOA. He viewed the SOA as a "surface in some multidimensional parameter space." [Ref. 16]

Martino stated that an SOA advance was a prerequisite before designers could move to higher surfaces. He reasoned that designers were constrained by technology and economics to stay on the SOA surface. As a result, improving the value of one technical parameter, such as speed, meant sacrifice of another parameter, such as weight. He examined several technologies to see if the data values on a surface had a discernible or random pattern. His goal was to determine the actual variables involved in design tradeoffs.

Martino's theories drew heavily from Dodson's work except for two statistical differences:

1. Martino extended his method to allow ellipsoid surfaces of any order, not just level two.
2. Martino's surface fitting procedure was changed to minimize the Mean Absolute Deviation rather than Mean Square Deviation.

He felt Dodson's fitting method was prejudiced by extreme date values.

Martino applied his surface-fitting procedures to clipper sailing ships, jet engines, propeller-driven aircraft, and power transistors. In selection of variables, he avoided the problem of scale effects by using nondimensional variables. For example, he divided a size variable by a "characteristic length" to cancel out scale effects. He also utilized "data triplets", where two positively correlated variables negatively correlated with a third variable.

Martino's primary results were that:

1. Deviations from the SOA surface could be explained quantitatively by known characteristics.
2. Different configurations representing the same SOA belonged on the same surface.
3. An engineering analysis was necessary in order

to select the proper variables. Designers were asked what parameters they worked on to improve.

4. The tradeoff surface technique worked for all levels of the Work Breakdown Structure.

In the next section, Dr. Dodson's 1985 update of his SOA measurement theory is discussed.

K. DODSON'S MEASUREMENT OF SOA AND TECHNOLOGICAL ADVANCE

Dr. Dodson's paper for the Workshop on Technology Measurement, Dayton, Ohio (12-14 October 1983), was published in 1985. [Ref. 17] This paper summarized his earlier works from 1969 to 1977. Also, he included two other approaches used to measure SOA advance.

Dodson described the factor analysis approach, a statistical technique for analyzing variance. He felt that factor analysis would help in identifying the underlying relationships of the many physical and performance characteristics of components. For example, he used factor analysis to rank sixty rocket motors by "Technological Distance Scores". He gathered data from the Chemical Propulsion Information Agency Rocket Manual for the following nine variables:

1. Delivered specific impulse.
2. Mass ratio (propellant weight/ motor weight).
3. Length-to-diameter ratio.
4. Reciprocal of burn time.
5. Motor weight.
6. Average thrust/ burn time squared.
7. Average thrust.
8. Average chamber pressure.
9. Date of development completion.

The factor analysis for the nine variables was able to account for eighty-three percent of the total variance of these variables. From the computed Technological Distance Scores, Dodson demonstrated graphically in this paper the effects of changes in mission requirements and technological capabilities. For example, the mission objectives for the Sprint missile required fast burning motors. Overall, this missile represented a significant technological advance.

His second new approach to measurement of SOA focused on the time available to develop levels of technology. His results revealed that for a given number of years, the higher the desired technology, the greater the risk. Conversely,the more time available, the lower the risk. However, Dodson's research has not extended this variant of the time factor into specific examples of SOA measurement. His paper indicates that application of this feature to multiparameter SOA surface equations must be a subject of future study.

L. MODELING RESEARCH AND DEVELOPMENT RESOURCE ALLOCATION

Cooley, Hehmeyer, and Sweeney developed the Technology Resource Allocation Model (TRAM) to analyze the impact of project selection, funding, scheduling, technical risk, and staffing upon an organization's research goals. [Ref. 18] Cooley's model was designed to answer what-if questions such as : what performance degradation could be expected if a five year development period was shortened to three years? The important design considerations in this model were: realism, model flexibility, ease of use, and output format. TRAM produced both tables and graphs which plotted the expected progress of the research effort as a function of time.

TRAM was structured to allow variability by analysts in the following factors:

1. Required funding by work unit.
2. Actual funding by work unit.
3. Probability of success by work unit.
4. Engineer manager work load by engineer manager.
5. Contribution factor for each work unit.
6. Schedule extension by work unit.
7. Performance objectives by work unit.

Cooley's model included consideration of the S curve effects. S curves normally depicted transpiration of relatively long lead times before significant results were achieved.

TRAM enabled the researcher to quickly analyze the effects of budget reductions on state-of-the-art development projects. Different measures of effectiveness were generated by variances of cost, schedule, and performance criteria. The sensitivity analysis for TRAM was accomplished through use of the DYNAMO Compiler.

M. MANAGEMENT CONTROL OF NEW PRODUCT DEVELOPMENT PROJECTS

McDonough felt management control systems were an essential ingredient in the success of state-of-the-art development projects. [Ref. 19] His research found that management control directly impacted SOA projects in the following ways:

1. Accuracy of cost and duration estimates.
2. Rate of progress of the SOA project.
3. Size of the development budget.
4. Quality of the output.
5. Competitive ability of the organization.

McDonough's paper identified the characteristics of effective management control systems. He also identified deficiencies common to most research and development organizations.

McDonough surveyed twelve large new product development projects. He found four elements common to all SOA developments. The first element was setting goals for new product projects. He found the primary goals were cost budgets and schedules. McDonough's results revealed that pressure from the Marketing Department forced the majority of project leaders to submit unrealistic low cost and duration estimates. He also found product specifications were of more concern to top management than budget or schedule overages.

McDonough's second element was the monitoring of project progress. Companies surveyed used three devices to monitor projects: written reports, formal meetings, and informal meetings. He found written reports and formal meetings had drawbacks in timeliness and detail for highly innovative technology-based projects. The personal monitoring of projects by top management via informal methods was the only way to quickly remedy new problems.

McDonough's third critical element was management's response to deviations from schedules and budgets. He found most companies reluctant to take action on technical issues of SOA projects. Their most common solution was to simply assign more engineers, an action that results indicated rarely provided desired effects.

McDonough's fourth element for management control systems was incentive provisions for performance. He found management rarely tied individual rewards to the attainment of budget and schedule goals.

In summary, McDonough stated the "management by walking around" was the key to successfully controlling new SOA projects. He also recommended bonuses to project managers who met budgets and schedules.

N. SUMMARIZATION OF RULES FOR BETTER ESTIMATES

Smith's paper provided an overall summary on the research and application of time, cost, and resource estimating. [Ref. 20] He developed rules for generating better estimates applicable to any project. The following list presents Smith's key factors necessary for the estimating process:

1. Level of Detail: provide a more detailed description via increased levels of the work breakdown structure.
2. Precise knowledge of the task being estimated.
3. Competency and knowledge of the process being estimated.
4. Importance of the estimate: estimates must appreciate significance.
5. Common units: all cost estimates should reflect the same dimensions.
6. Uncertainty: estimates should indicate measures of the maximum possible error.
7. Assumptions should be explicitly stated.
8. Uncontrollable variables should be incorporated.

Smith felt estimates could be improved by use of more than one technique, such as estimating by analogy, firm quotes, handbook estimating, parametric estimating, or regression analysis. He also stated that relevant historical data was often overlooked. He stressed the importance of detail in the work breakdown structure, so errors in one estimate would not have a great aggregate effect. Finally, Smith stated management could use certified professional estimators for uncertain projects, since they would possess increased appreciation for the repercussions of estimates on the baseline plan.

O. EVALUATION OF KEY SOFTWARE COST ESTIMATING MODELS

In 1981, Thibodeau performed the Air Force's first large scale study of the various software cost estimating models used to make estimates of the resources to be invested in the software subsystems. [Ref. 21] Thibodeau recognized that hardware cost estimating was more advanced, possessing more identifiable measures of size and performance which had been correlated with cost. He found there were no reliable procedures for quantitatively describing the effects of non-product factors on cost.

Thibodeau evaluated and provided descriptions for the following models: Aerospace, Boeing, DOD Micro Estimating, Doty Associates, Tecolote, Wolverton, PRICE S, SLIM, and Farr and Zagorski. He provided one page summaries for each model type, including descriptions of the estimating procedure, characterization of productivity, and outputs.

Thibodeau's comparison of the outputs indicated

1. Supporting materials for the models did not precisely state the elements included in their estimates.
2. The models were more adept at satisfying information early in the acquisition life cycle.
3. The models were acquisition phase oriented and did not describe activities that crossed different phases.
4. Only PRICE S kept track of the cost on a component basis and accounted for the cost of

system integration. However, none of the models could provide costs for every level called for in the Work Breakdown Structure.

Thibodeau measured performance based on the relative root mean square error. He found:

1. Recalibration was the primary contributor to differences in model estimating performance.
2. The structure of the model was not significant to estimating accuracy.
3. The development environment significantly influenced the performance of the cost estimating models.
4. The use of size as an input had no effect on the relative performance of the models.
5. The average root mean square estimating error was between fifteen to thirty percent.

In his final section, Thibodeau provided recommendations for future model development and better data definition and collection. Finally, Thibodeau described the derivation of technology and complexity factors for each of the nine surveyed cost estimating models.

P. SUMMARY

Chapter Two described a sampling of background literature relevant to measurement and control of SOA advance development projects. Chapter Three presents examples of a few specific hardware cost estimating models utilized by General Research Corporation and the Air Force.

III. DEVELOPMENT OF COST ESTIMATING MODELS

A. INTRODUCTION

Chapter Three describes the development of four cost estimating models, including three specific ones derived exclusively for weapons systems. For each model the general methodology is highlighted, followed by sample cost derivations for various cost elements. The four models examined are:

1. Dodson's cost estimating models for ground combat surveillance radars (1968).
2. Dodson's cost estimating methods for the High-Energy Laser Systems Cost Model (1979).
3. The Unmanned Spacecraft Cost Model (1981).
4. The Freiman Analysis of Systems Technique (FAST).

B. GROUND COMBAT SURVEILLANCE RADARS

Dr. E.N. Dodson developed cost estimating methods for ground combat surveillance (GCS) radars during a study for the U.S. Army Electronics Command in 1968. The basic methodology is still applicable to larger, more current system studies. The goal of Dr. Dodson's model was to provide Army comptrollers with a model to evaluate contractor cost estimates. [Ref. 22]

Dodson's GCS radar model considered state of the art limitations. He stated that the major objective in the design of GCS radars was to achieve minimum weight for a specified performance. He used maximum range as the crude measure of radar performance. To prevent development and production cost penalties, Dodson's study indicated that radar design engineers imposed constraints that radars to be costed should not be improved by more than five percent over the original SOA curve.

To derive the model, Dodson first collected data on twenty input variables. He utilized the work breakdown structure, disaggregating each life cycle element into a set of functional subsystems. The life cycle elements were designated as engineering development, advanced production engineering, and production. The work breakdown structure for engineering development, for example, was broken down further into hardware fabrication and documentation.

In Dodson's next step, he derived a cost estimating relationship for each category in the work breakdown structure. The cost estimating functions were derived through the following basic steps:

1. All known factors between the variables of interest were specified.
2. Regression equations were developed through a sequence of known intermediate relationships. The mechanisms by which an item's physical characteristics affected raw material quantities and labor hours were investigated. Engineering information related the functional variables of interest to the physical configuration.
3. Standard curve fitting techniques determined the constants associated with the regression equations.
4. The statistical properties of the resulting correlation were measured.

Dodson claimed the model's results provided no more than a basis for judgment, since previously confirmed observations were his only data source. Also, he did not have enough data to allow estimation of confidence intervals for his cost predictions.

During the model's development stage, Dodson gathered cost data from seven different radars. He used a price index developed at General Research Corporation to normalize the dollar price data to 1966 levels. His index assumed an equal breakdown of engineering labor, production labor, metals and hardware, and electrical equipment.

Dodson utilized learning curve assumptions to normalize cost data with respect to different production quantities. For both complete radar sets and subsystems he used a slope value of ninety percent.

The GCS cost model was composed of the aggregate estimating relationships for each element. Dodson derived production costs first, using the production cost per unit as an input variable to the engineering models. No more than two or three input variables were required to use any one relationship.

The model input variable for production included:

1. Type of design, either pulsed or FMCW.
2. Number of radars in the first production lot.
3. Type of antenna material, either aluminum or fiber glass.
4. Antenna frontal area in square feet.
5. Center frequency in megahertz.
6. Peak radiated power.
7. Range resolution.
8. Type of presentation, such as handset, loudspeaker, or plotter board.
9. Total radar set weight.
10. Prime power source, either battery or motor-generated.

The only inputs required for engineering development were cumulative average production cost and number of development models fabricated.

Dodson derived advanced production engineering costs from the cumulative average production cost, number of prototype models fabricated, and the number of radars to be produced in the first production lot. The model was built from actual production cost data describing the various subsystems. Subsystems included antennas, scanheads, microwaves, transmitters, receivers, presentation and control, chassis, interconnections, casings, and tripods.

Dodson derived a regression equation to estimate the microwave subsystem of a radar. He defined the microwave subsystem as a "collection of switching and waveguide components that carries microwave signals between the transmitter and antenna, and the antenna and receiver." [Ref. 23] The key input variables researched were frequency and peak radiated power. His final model for microwave cost was derived by adding the fixed waveguide cost at each frequency to the power-dependent duplexer (switching) cost. The cost estimating relationship for pulsed microwaves was found through regression analysis to be:

$1100 + $9.4 P, with "P" equal to kilowatts.

Dodson collected cost estimates for all production subsystems, such as the microwave, to obtain total subsystem cost. Next, he added on the final assembly and test cost to obtain the cumulative average radar set cost. The learning curve factor then adjusted the total cumulative average radar set cost. The prime power cost was added to the previous sum to obtain the cumulative average cost for prime power hardware. Finally, the above total was multiplied by one hundred five percent to account for the additional cost of technical data. The result was the cumulative average radar production cost.

Engineering development costs were calculated by multiplying the cumulative average radar production costs by a factor of three to get the cumulative average cost for development hardware. He based this factor of three on the historical trends of the seven systems studied and consultation with industry experts. The learning curve factor was applied with the number of units to obtain the cumulative total development hardware cost. An additional fifteen percent was added on to account for the extra cost of documentation.

Dodson's model also provided a hierarchy of estimating systems, depending on the data available to the analyst. He recommended all information sources be exhausted before reliance on estimates based solely on the regression equations.

The next section provides a brief overview of the laser system cost model developed by Dodson a decade later.

C. HIGH-ENERGY LASER SYSTEMS COST MODEL

In June 1979, Dr. E.N. Dodson completed a study for the U.S. Air Force to develop a comprehensive life-cycle cost model for high-energy laser weapons systems. [Ref. 24] The study accomplished the following objectives:

1. Created a cost data base for laser weapons systems.
2. Developed cost estimating relationships for laser weapons systems.
3. Integrated the cost estimating relationships into a life-cycle cost model.
4. Used the cost model to project costs for a number of weapon system concepts.

Laser weapons systems were required to detect a target and establish its position. This knowledge enabled the high-energy laser beams to be properly directed. Other system requirements were target identification, threat assessment, firing doctrine, kill assessment, plus miscellaneous support equipment.

Dodson relied on the parametric method to develop cost-estimating relationships for the laser systems. Since laser systems had never been produced previously, he used two different approaches to gather the necessary data. First, he used analogous equipment of similar physical complexity for analysis. For example, liquid-propellant rocket motors were considered similar to a laser device's mechanical elements. Also, Dodson gathered cost estimates for laser subsystems by currently active contractors in the field.

Additional modeling considerations included an assessment of mission performance. Performance was considered a system parameter measured at the aggregated level of equipment detail. He developed performance-cost relationships for particular types of designs at the aggregate level. Dodson's model was capable of updating the performance-cost relationships with changes from new technological developments. Examples of performance criteria for lasers were radar detection range, laser power, mission kill probability, and energy density on target.

Dodson's next consideration in model development was the synthesis of the individual cost estimating relationships into the overall cost model. He recognized they must cover all costs of interest. Also, costs were defined so that double-counting was avoided. He also defined all units in dollars of the same purchasing power.

Dodson based the Work Breakdown Structure for this study on the life-cycle elements of the Demonstration and Validation, Full Scale Development, Production, and

Operations and Support acquisition phases. The first two phases separated recurring and nonrecurring costs. Recurring costs represented those costs directly associated with the fabrication of prototypes. Nonrecurring costs included all other costs, primarily engineering design and component testing costs.

All cost relationships were presented in thousands of 1976 dollars. Provisions for translating those cost figures into specified future year constant dollars were included.

The cost elements at the bottom levels of the Work Breakdown Structure included the hardware associated with the laser systems with other cost elements such as system test and evaluation and project management.

Computer subroutines developed by Dodson enabled the model to carry out types of calculations common to a number of high-energy laser subsystems. The required inputs to the high-energy laser systems cost model included:

1. Choice of laser type, like chemical or gas dynamic.
2. Device output power in watts.
3. Specific power in kilojoules per pound.
4. Number of laser shots per mission load.
5. Shot time in seconds per pulse.
6. Pulse recurrence frequency in pulses per second.
7. Electrical efficiency, consisting of device output power divided by prime electric power.
8. Output beam diameter in centimeters.
9. Number of turrets per aircraft.
10. Number of adaptive optics actuators per mirror.
11. Number of flight hours.

The model also provided optional inputs to the user. The user could choose among different procedures for calculating fluids costs, avionics costs, or operations and support costs. For example, for fluids the user provided the flow rate for each fluid, which was then combined with cost and lasing time information to establish total fluid costs. If flow rates were not available, the model could assimilate the values of specific power and lasing time with internally-stored information about the proportions of individual fluids and their costs, to determine total fluid costs. Tables with the numerous characteristics for fluids were provided in the model. Fluids represented a variety of individual reactants and diluents used in high energy laser systems. The primary characteristics contained were cost-per-pound figures.

The High-Energy Laser Systems Cost Model provided the following outputs:

1. Listing of user provided system inputs.
2. List of Avionics inputs as selected by the user.
3. Intermediate set of results for fluids, including calculated values of weights and costs for individual fluids.
4. Printout of fluid-usage parameters for the individual fluids selected for the case under study.
5. Listing of the Operating and Support cost parameters used in calculating these costs.
6. Detailed presentation of life-cycle costs by cost element in the Work Breakdown Structure.

Costs were presented in thousands of constant-dollars based on 1976 as the base year. Successive levels of aggregation were shown in the cost model. The model also summarized by cost element the individual cost estimating equations utilized.

The following example highlights Dodson's model. The validation phase, one of the four life-cycle phases, consisted of nonrecurring and recurring costs. Nonrecurring costs were the sum of these elements:

1. Airborne system costs, which included:
   a. Device costs.
   b. Power supply costs.
   c. Fluid supply costs.
   d. Optics, pointing, and tracking costs.
   e. Avionics costs.
2. Aircraft modifications costs.
3. System test and evaluation costs.
4. Project management costs.

The device cost for airborne systems was the sum of individual costs developed for the device, diffuser/ejector, and associated instrumentation controls, along with auxiliary power elements. The mathematical cost estimating relationship generated for chemical laser devices was cost equalled 15.309 times device output power (watts). Device output power was first scaled to the .44 power.

Dodson's model did not express separately SOA extension costs. In the next section, the Air Force Spacecraft model is discussed, with particular emphasis on the use of engineering design complexity.

D. UNMANNED SPACECRAFT COST MODEL

The 1981 edition of the Space Division Unmanned Spacecraft Cost Model is considered by the aerospace industry estimating community as the most widely applied spacecraft cost estimating tool. [Ref. 25] The model's purpose is to collect historical cost data for use in a parametric cost estimating relationship framework. The model is used to formulate more responsive cost estimates for long range planning studies and future spacecraft systems.

The model is organized into a data matrix. The matrix is subdivided into areas of activity, subdivisions of work, and elements of cost. Areas of activity are specific or general hardware classifications, such as aerospace ground equipment. Subdivisions of work indicate processes associated with more than one hardware item, such as design or fabrication Elements of cost represent the standard cost accounting categories of engineering labor, material costs, manufacturing overhead, and general and administrative expenses.

The subdivisions of work are identified as nonrecurring and recurring costs. A time-phased method determines the break between the two types of effort. Nonrecurring costs begin with concept development and stop when the qualification test of the prototype is complete.

Three examples of the areas of activity are the platform, electrical power supply,and the attitude control. The platform is part of the spacecraft structure, and bears the majority of spacecraft dynamic stress loads. Examples of cost drivers for the platform are: structure weight, volume, and mass density. The electrical power supply generates, converts, and distributes all electrical energy between spacecraft components. Examples of cost drivers are electrical power supply weight, battery weight, total vacuum impulse, and action time.

The attitude control system maintains the spacecraft in the required orbit. The system can be stratified into three design categories or two functional categories of equipment. Cost drivers are dry weight, wet weight (with fuel), total impulse, operating life, angular drift, and altitude.

The ground rules for the cost model are:

1. The model addresses only unmanned earth-orbiting spacecraft.
2. Cost estimating relationships are obtained by relating costs at the subsystem level to physical and performance characteristics.
3. All cost estimating relationships are based upon burdened costs, so the model consists of the total cost through general and administrative expense cost estimating relationships.
4. A ninety-five percent average learning curve is used to derive unit costs.
5. The cost estimate is expressed in 1979 constant dollars.

Based on the ground rules, starting point cost estimating relationships are generated. For the three areas of activities considered earlier, the derived regression equations were:

1. Platform costs = 7414.46 + 22.6 X, with X representing platform dry weight in pounds.
2. Electrical Power Supply costs = 360.97 + .0165 X, with X representing the product of electrical power supply weight and beginning of life power in watts.
3. Attitude Control costs for the attitude and reaction control subsystem = 426.49 + 31.47 X, with X representing the dry weight of the attitude and reaction control.

The cost estimating relationships listed above were derived after examining all program cost data on scatter diagrams. Next, regression analysis was performed for several parameters. Further analysis was performed on the cost drivers which significantly influenced cost. Transformations were performed on selected variables via multiplication, square roots, or logarithms to create synthetic variables in an effort to find the most influential cost drivers. Finally, the data was stratified for all data points to determine homogeneity of the points.

Once the cost estimating relationships were generated, they were normalized to account for inflation, influences of alternate design concepts and new technological breakthroughs. In the normalization process, actual cost data are evaluated with respect to quantifiable subjective parameters. The parameters enable the actual cost data to be adjusted to a common base at the subsystem level. Two subjective parameters selected were technology carryover and complexity of design.

The technology carryover cost factor measures the state-of-the-art of technology at different periods of time. The technology carryover measurement scale is divided into five levels to capture the degree of engineering learning over time. The five levels are:

1. 1.00: the item is substantially beyond the SOA.
2. .75: the item is slightly beyond the SOA.
3. .50: the item is within the SOA but no commercial counterpart exists.
4. .25: the item will involve a minor modification of commercial items.
5. .10: the item will be procured off-the-shelf.

Programs can be examined by the Unmanned Spacecraft Cost Model by the complexity of design cost factor also. The first step is to identify subsystem operational criteria which could relate cost to the degree of complexity. Descriptors must be chosen to realistically assess the operational criteria. Each operational criterion is ranked against a base value of 100 percent. The evaluation is compared to the subsystem complexity factor matrix. The relative ranking indicates the degree to which the operational criteria affects the costs of developing the subsystem.

To obtain the normalization cost factors, a comprehensive study of industry experts was conducted. A weighting scheme was devised to generate one normalization factor for each subsystem from the composite of technology carryover, complexity of design, and inflation factors. Each subsystem's raw cost data points from the initial cost estimating relationships were divided by the composite normalization factor to yield a set of normalized cost data points. The normalized cost will always be less than the initial point design cost estimate.

The normalized cost estimating relationships enable the cost analyst to perform trade-off studies for near-term conceptual programs. They permit calculation of costs for more specific spacecraft programs. The Unmanned Spacecraft Cost Model via an appendix provides a summary of all the normalized cost estimating relationships.

The next section outlines the basic concepts behind the Freiman Analysis of Systems Technique (FAST), developed by Frank Freiman. [Ref.26]

E. FREIMAN ANALYSIS OF SYSTEMS TECHNIQUE (FAST)

Freiman developed the FAST parametric cost estimating system to evaluate the cost impact of variations in schedule or design. Freiman's system differs from the conventional parametric models, such as the Unmanned Spacecraft Cost Model, in the following ways:

1. It quantifies technological phenomena underlying design which cause costs to vary with size and design.
2. It reduces need for lengthy historical design versus cost records.
3. It allows synthesized data points to be used for initial development estimates.

The FAST methodology involves analysis of the fundamental concepts behind technology variance with cost per pound. Freiman found advanced SOA technologies provide more energy per unit of design mass than those within the SOA. The same performance for SOA extensions can be accomplished with less equipment mass. Freiman's theory is that to advance a design mass, more energy per pound must be utilized.

The FAST model estimates costs by its class of technology. Its seven basic types, in hierarchial order, are electronic, electrical, heat, motion, mechanical control, containment, and support. Freiman also used the weighted average level of the technology with the degree of performance desired to categorize equipment types by design mass components. His five basic types of design masses are:

1. Energy Conversion Mass - converts one energy form to another.
2. Design Overhead Mass - added due to inefficiencies of design.
3. Application Mass - required to transfer energy.
4. Dimensional Mass - required for physical coverage of a system.
5. Conditional Mass - required for environmental or personnel safety reasons.

Based upon the design mass and technology type, FAST can quantify cost per pound of the electronic system being estimated. Via computerized mathematical equations the cost estimating relationships among cost, weight, and technological complexity can be expressed.

FAST also simulates the thought processes of successful managers. FAST's methodology is derived from the way managers intuitively assess the cost of SOA advancements. FAST is designed to simulate behavioral responses ranging from establishing the data base to exercising "what-if" capabilities.

FAST systems feature the following:

1. Accept tailored inputs from varied design and manufacturing circumstances.
2. Project funding requirements via graphic and alpha-numeric displays.
3. Provide risk measurement through display of cost uncertainties for each cost segment.
4. List detailed complexity values for commercial and industrial items.
5. Are user-friendly, unlike the more specific cost models such as the ground surveillance radar cost model.

FAST is useful as a check for conceptual stage cost estimates, although it must be calibrated for each individual user. Tables 1 and 2 represent sample outputs for the FAST cost estimating model for electronic equipment. Table 1 is divided into five primary sections, broken down as follows:

1. Total estimated costs of the line item, with subtotals for engineering, production, and installation costs. If necessary, costs for schedule delay could be included.
2. Cost uncertainty distributions, for risk

evaluation. Three confidence intervals, ranging from seventy to ninety percent are shown for the engineering, production, and installation subtotals. Note the total assumes the covariance equals one.

3. Characteristics of the equipment's energy sources. The primary energy required is expressed in kilowatts, while secondary items such as pressure and temperature are also summarized. A synthetic FAST energy variable is calculated and shown below the primary and secondary characteristics.
4. Production cost data, using average unit costs. Figures for the total estimated production costs, manufacturing costs, and the theoretical forecast are shown. In this example manufacturing costs are the same as production costs, due to lack of beginning work in process inventory.
5. Input data. The factors actually entered by the cost estimator are presented. Among the inputs are:
   a. PRJGLOB: Overall project global inputs are shown. This line requires an escalation control factor for inflation, the year of economics to be used, learning curve factor, and a cost multiplier index.
   b. FILE and FORMAT input different types of system options.
   c. GLOB - Further global inputs are included, specifically the platform specification level, engineering design mass type, year of technology to be used in production, and a weighted energy value based on kilowatts,

british thermal units, pressure, and temperature.

d. WTVOL: Weight and volume factors, along with their weighted values, are shown.

e. MXLINE: Manufacturing complexity values for the production of the line item are given.

f. PCOST, ECOST, ICOST : Inputs for basic costs of production, engineering and installation, along with quantities and the year of economics, are shown.

g. PSCHD, ESCHD, ISCHD : Values for start and completion dates, complexity values, and skill levels are presented for production, engineering, and installation schedule factors.

h. PLOH, ELOH, ILOH : Production, engineering, and installation material, manufacturing overhead, labor, and indirect labor factors, along with an aggregate labor rate for each phase, is presented.

Table 2 shows the cost distribution by total labor hours for engineering, production, and installation. Also, a production profile graph compares the cumulative funding for the project against the estimated cumulative expenditures, by quarters from 1984 to 1991. The expenditures indicate actual disbursement of manufacturing costs, while funding indicate the budgeted figures.

F. SUMMARY

This section highlighted features of four different cost estimation models. Chapter Four presents the case study description of Litton Applied Technology's cost estimating process for the AN/ALR-67 Radar Warning System.

TABLE 1

```
***** FAST-E *****

PROJECT:  TEST UNIT                          DATE: MON, JUL 14 1986  09:59 23
LOCATION: GERMANTOWN,MD                      FILENAME: FASTE.EXAMPLE
ITEM:     DETAIL                             ECONFILE:

                         ***** DETAIL ITEM *****

        $UNITS  =     1,000 BASIC COST   SCHD PENALTY      TOTAL COST
          ENGINEERING          797.19            0.00          797.19
          PRODUCTION         1,301.45            0.00        1,301.45
          INSTALLATION         519.84            0.00          519.84
           TOTAL ACQ.        2,618.48            0.00        2,618.48

                  ***** COST UNCERTAINTY DISTRIBUTION *****

           -FROM-  70% -TO-       -FROM-  80% -TO-       -FROM-  90% -TO-
ENG           723       871          680       914          619       975
PROD        1,227     1,376        1,184     1,419        1,123     1,480
INST          476       564          450       590          413       626
 TOT        2,427     2,810        2,314     2,923        2,155     3,082

                        ***** CHARACTERISTICS *****

                 PRIMARY              VARIABLE         QUANTITY
                 KILOWATT             (PKW    )         250.000

                 SECONDARY
                 BRITISH TH. UNIT     (SBTU   )       1,500.000
                 PRESSURE (PSI)       (SPRESS)           50.000
                 TEMPERATURE (F)      (STEMP )          125.000

                 FASTE EQUIVALENT
                 FASTE                                  957.136*
                   TENVLE(FASTE)                      FAS.0.248*

                    ***** PRODUCTION COST DATA *****

             AVERAGE UNIT COSTS BASED ON:
        TOTAL PRODUCTION COST  MANUFACTURING COST  THEORETICAL FPCOST
              26,029.03             26,029.03             40,466.78

                         ***** INPUT DATA *****

                  ESCAL      GECON      FPER      LCURVE          CMULT
PRJGLOB           1.000      1989       OCT        0.900          1,000.
                  TYPE       SYSTEM     RERUN     REMBOX
FILE              0            0        0           0
                  ALL    COST   UNCERT  LOHMAT  INPUT    FGRAPH   FDET
FORMAT             1      0        0       0      0         0       0

                  PLTFM   ENTYPE MATVAL  TYEAR                 TENVAL
GLOB              1.300   70.000   1.00   1988       KW.BTU.PRS.TEM.0.207

                  WT         WTFAC          VOL        VOLFAC
WTVOL          1,060.70*     350.00        24.15*     100.00
                  PMX        MXTYPE      ELWT     ELMX            STWT    STMX
MXLINE            0.200      4.280*       0.0     0.000            0.0    0.00

                  PCOST                 PQTY      PECON      FOAK
PCOST           1,301.45*                50.       1989      1.000
                  PSTART     PFIN       PSCHDX    PRDMX      PYEARC     PDISC
PSCHD             DEC.1989   NOV.1991*  100.00    3.327*      1989*     NONE
                  PMATL      PMOH       PLABOR    PLOH       PLRATE
PLOH               0.30       0.00       0.34*     1.06*      11.75
                  ECOST      EQTY       EECON     EMX        ENEW
ECOST            797.19*      5.2        1989     0.850       0.700
                  ESTART     EFIN       ESCHDX    ELEVEL     EYEARC     EDISC
ESCHD             JUN.1988   OCT.1989   121.43*   0.700       1989*     NONE
                  EMATL      EMOH       ELABOR    ELOH       ELRATE
ELOH               0.35       0.00       0.26*     1.48*      22.55
                  ICOST      IQTY       IECON     IMX
ICOST            519.84*      50.        1989     1.250
                  ISTART     IFIN       ISCHDX    ILEVEL     IYEARC     IDISC
ISCHD             JUL.1990   FEB.1991*   80.00    1.000       1989*     NONE
                  IMATL      IMOH       ILABOR    ILOH       ILRATE
ILOH               0.15       0.00       0.46*     0.85*      13.40
                  CONTIN     ADD
END                0          0
```

TABLE 2

***** COST DISTRIBUTION *****

	ENGINEERING	PRODUCTION	INSTALLATION	TOTAL
LABOR (HRS)	(9,283.58)	(37,572.70)	(27,868.99)	(64,725.27)
COST	209.34	441.48	239.44	890.27
OVHD	308.83	469.54	202.42	980.79
ST	518.18	911.02	441.86	1,871.06
MATL	279.02	390.44	77.98	747.43
OVHD	0.00	0.00	0.00	0.00
ST	279.02	390.44	77.98	747.43
TOT	797.19	1,301.45	519.84	2,618.48

***** FAST-E *****

PROJECT: TEST UNIT
LOCATION: GERMANTOWN,MD
ITEM: DETAIL

DATE: MON, JUL 14 1986 09:59:58
FILENAME: FASTE.EXAMPLE
ECONFILE:

***** DETAIL ITEM *****

***** PRODUCTION PROFILE *****

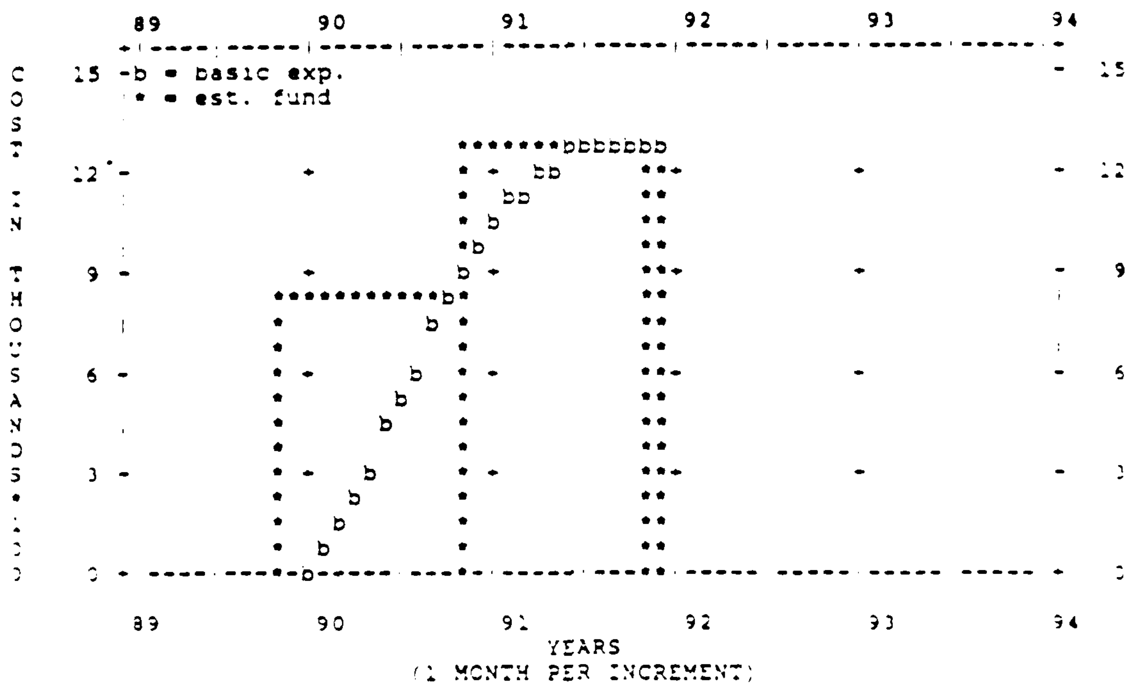

TABLE [illegible] (CONT.)

***** ESTIMATED PROJECT PROFILE *****
(COST IN THOUSANDS)

MONTH	YEAR	CUM. FUNDINGS	CUM. EXPENDITURES
OCT	1989	816.3	0.0
JAN	1990	816.3	66.4
APR	1990	816.3	321.2
JUL	1990	816.3	628.5
OCT	1990	1,295.3	899.2
JAN	1991	1,295.3	1,095.5
APR	1991	1,295.3	1,215.4
JUL	1991	1,295.3	1,276.5
OCT	1991	1,301.5	1,299.9
NOV	1991	1,301.5	1,301.5

***** ESTIMATED FUNDINGS *****
(COST IN THOUSANDS)

MONTH	YEAR	FUNDINGS
OCT	1989	816.3
OCT	1990	479.1
OCT	1991	6.1

***** PRODUCTION QUANTITY BY FISCAL YEAR *****

YEAR ENDING MONTH	YEAR	FISCAL QTY
SEP	1990	1
SEP	1991	48
SEP	1992	1
TOTAL		50

IV. DESCRIPTION OF LITTON APPLIED TECHNOLOGY'S COST ESTIMATING SYSTEM

A. INTRODUCTION

This chapter describes Litton Applied Technology's cost estimating system for development projects which extend technology beyond the SOA. This case study will primarily focus on the AN/ALR-67 Radar Warning Receiver, also called the Advanced Countermeasures Control and Warning System. The chapter is divided into the following sections:

1. Litton's background in development of radar warning receivers.
2. Description of key physical and performance characteristics of the AN/ALR-67 Radar Warning Receiver.
3. Litton's pricing and estimation system.
4. Cost estimation methodology for derivation of direct costs.
5. Delineation of actual costs incurred by Litton from development through initial production for the AN/ALR-67 Radar Warning Receiver.

B. BACKGROUND FOR RADAR WARNING RECEIVERS

1. General Background

Litton Applied Technology is a division of Litton's Electronic Warfare Systems Group. Currently located in south San Jose, California, Litton Applied Technology employs approximately 1800 people in the research, design, manufacture, and support of defense electronics systems. Besides radar warning receivers, they also specialize in integrated electronic warfare systems, space and strategic defense systems, and flight training and operational simulation systems.

Applied Technology actually was an independent company until 1983, when it became a division of Litton.

2. History of Radar Warning Receivers

Applied Technology first became involved with radar warning receivers in 1965. The concept of radar warning receivers was initiated by a special Air Force task force commissioned to develop methods to counter Soviet surface-to-air missiles. In 1965, North Vietnam developed a complex air defense system closely coordinated through the use of communications and radar, based on Soviet technology. The Air Force's research committee reviewed new concepts for warning and jamming equipment which could counter the North Vietnamese air defense threat. In November 1965, Applied Technology received a six million dollar production contract for 500 AN/APR-25 Radar Warning Receivers from the USAF Sacramento Air Material Area. The contract was Applied Technology's first major production contract, since previous defense experience was limited to technology applications for intelligence programs, where large production runs consisted of only ten units.

The design philosophy for the AN/APR-25 centered on gathering as much signal information as possible. Crystal-video detection techniques were used in the threat bands to determine the hostile equipment's relative direction.

In the late 1960's Applied Technology updated the AN/APR-25 with the AN/APR-35 Radar Warning Receiver. New technology such as automatic time/video correlation circuits and a new superheterodyne analysis receiver were added. Also, improvements in operator interfaces were added to the equipment to enable the Electronic Warfare Officer to instantaneously communicate to the pilot which directions surface-to-air missiles were fired from.

The next generation of radar warning receivers was introduced in 1970, based on the new Soviet threat to the Mediterranean region. The AN/ALR-45 became the first digital system to incorporate hybrid microcircuits using digital logic and clock drivers. This generation's design philosophy emphasized the need for sorting analysis of emitter types and prioritization of lethal pulses. Non-lethal threat information could now be discarded.

In 1971 Applied Technology, in a fundamental change, became deeply involved in computer design evolving from analog circuit design. In 1972 the company developed the Applied Technology Advanced Computer (ATAC) specifically for electronic warfare. This computer was capable of being reprogrammed at a squadron level. The ATAC computer's volume was 96 cubic inches, with power consumption 45 watts, and an input/output rate of 1.25 megawords per second.

In 1975, the ATAC computer was used in the development of the AN/ALR-67 threat warning program. Integrated power management systems now collect and analyze multiple threats to enable optimum jamming. The AN/ALR-67 was developed due to the Navy's need for increased speed and prioritized threat warning information. The AN/ALR-67 is now deployed on the F/A-18A, CF-18, F-14A, F-14B, A-6E, A-6F, AND AV-8B aircraft.

The next generation of radar warning receivers to be fully deployed will be the AN/ALR-74 threat warning systems, as of 1987. The AN/ALR-67 is completing the full-scale development phase.

C. PHYSICAL AND PERFORMANCE CHARACTERISTICS

The AN/ALR-67 Radar Warning Receiver's primary function is to notify the radar operator of the presence of threatening signals. The AN/ALR-67 is designed to inform the pilot of how many hostile radar systems are active in his flight area. The AN/ALR-67 identifies the type and relative location of each threatening radar signal.

The most important performance criterion of the AN/ALR-67 is response speed. The AN/ALR-67 is designed to allow the pilot time for evasive action against potential threats. Also, the radar warning receiver's response time is quick enough to provide accurate relative direction information on hostile threats immediately following aircraft maneuvers.

To be effective, the AN/ALR-67 must transmit the critical parameters of the threat to the aircraft jamming system in digital form. The effectiveness of the jammer's electronic countermeasures depends on the AN/ALR-67's receiver acquisition time.

The second performance criterion for the AN/ALR-67 is threat identification. The radar warning receiver characterizes hostile signals by their modulation characteristics and range of RF frequency operation. RF frequency pulse trains often occur simultaneously, so the AN/ALR-67 must be capable of unambiguous signal identification.

The AN/ALR-67 is also designed to look at selective frequency bands so high duty signals can be analyzed independently without interference. The pilot receives information from the AN/ALR-67 Radar Warning Receiver by visual displays on a three-inch diameter cathode ray tube in the cockpit. The pilot receives data as following from the AN/ALR-67.

1. Relative direction of each signal to an accuracy of 15 degrees to 30 degrees.
2. Indication of each signal's strength.
3. Identification by symbols of specific radar types.

The design of the AN/ALR-67 Radar Warning Receiver is constrained by three practical factors: volume, power consumption, and cost. The allocated volume for the radar warning receivers has remained constant since 1965. The increase in customer requirements and the continued development of electronics microwave techniques has led to high package density, which imposes the constraints on power consumption. Cost constraints must be met through system tradeoffs. A six decibel difference in receiver sensitivity requirements could mean the difference between development of crystal video receivers, or more expensive wideband superheterodyne receivers.

Processing of signals through the ATAC computer has replaced human interpretation of audio and visual information. The AN/ALR-67 has a tangential receiver sensitivity between -50 dBm and -60 dBm, at a 10 -MHZ video bandwidth. System sensitivity experiences losses due to cabling and filtering.

Search speed limitations place another constraint on the AN/ALR-67. The ratio of the RF frequency search band to the receiver instantaneous bandwidth determines the length of time it takes a receiver to intercept a potential signal.

The most recent advances in microprocessor technology enable radar warning receivers to have each element of the distributed receiver system to be controlled independently by a computer. The AN/ALR-67 was the first radar warning receiver to control its system operations via computer software.

The individual subsystem components of the AN/ALR-67 Radar Warning System are the:

1. Computer.
2. Azimuth indicator.
3. Control indicator.
4. Quadrant receiver.
5. Special receiver.
6. Receiver antenna.
7. Quadrant antenna.

Their size and weight characteristics are shown in Table 3.

TABLE 3

ALR-67 SIZE AND WEIGHT

WRA	NOMENCLATURE	L	W	H	WT. (LBS)
COMPUTER	CP-1293/ALR-67	16.5	4.89	7.59	28.0
AZIMUTH INDICATOR	IP-1276/ALR-67	6.94	3.25	3.25	3.5
CONTROL INDICATOR	C-10250/ALR-67	3.84	4.25	1.81	1.9
QUADRANT RECEIVER	R-2148/ALR-67	7.03	1.73	6.19	4.0 EACH
SPECIAL RECEIVER	R-2055/ALR-67	13.0	11.3	3.75	30.0
RECEIVER ANTENNA	AS-3190/ALR-67	8.0	6.75	3.12	11.3
QUADRANT ANTENNA	AS-3189/ALR-67	2.5	2.43	2.43	0.5 EACH

TOTAL ALR-67 (V)2 SYSTEM WT. 87.0 LBS.

D. LITTON APPLIED TECHNOLOGY'S COST ESTIMATING SYSTEM

Litton Applied Technology has developed a complex matrix structure to manage its proposal estimating system for government contracts such as the AN/ALR-67 Radar Warning Receiver. Its approach is designed to accommodate government procurement regulations, compliance with the Cost Accounting Standards, specific customer requirements, and its own company policies. The stated goal of their cost estimating system is to be systematic and consistent.

Litton's Proposal Pricing and Estimating Manual defines its five primary tasks as:

1. Define requirements in a manner which allows specific work elements to be performed.
2. Develop a work breakdown structure and cost matrix compatible with the cost collection system of the cost elements. The elements must be measurable and definable through task descriptions which are consistent with the statement of work requirements.
3. Identify and develop significant milestones and schedules for each work element and a realistic program schedule.
4. Prepare data to serve as the basis for the review of all cost estimates.
5. Review and present the related cost experience, historical data, and detailed cost estimates.

The Vice President of Business and Financial Operations has overall responsibility for Litton Applied Technology's cost estimation system. The two primary subordinates who assist him are the Director of Proposal Cost Estimating and Analysis and the Manager of Proposal Operations.

The Director of Proposal Cost Estimating and Analysis is primarily responsible for the development of cost proposals for division products. His division must establish and maintain effective cost estimating tools and techniques. He also ensures cost proposals comply with customers' cost proposal requirements and regulations. The division must support internal cost reviews and establish the budget baselines for the project cost control. The direct planning, monitoring, and prioritization of all cost proposal activities are conducted under his cognizance.

Litton Applied Technology's corporate guidelines hold the Director, Cost Estimating and Analysis directly accountable for:

1. Formulation of guidelines for all proposal pricing preparation and reviews in accordance with division policy.
2. Development of overall division cost proposal plans. He must define an schedule the prerequisite support from line management. The plans must cover the statement of work, basic assumptions, cost data, and problem identification and resolution. The conducting of reviews with line management on major cost proposals is included within this task.
3. Support of cost proposals during the customer's evaluation cycle. He must develop and establish negotiation cost positions. He also assigns and approves the members of the negotiating team. The director ensures cost updates and cost disclosures are in accordance with customer regulations.
4. Review current division cost performance trends to ensure that such performance is considered in all proposals.
5. Direct resources dedicated to the development and maintenance of the pricing data base. He is also

accountable for implementing advanced estimating techniques and systems for the division's proposals.

6. Support design-to-cost analysis projects of the division.

The Manager of Proposal Operations is accountable for managing Litton Applied Technology's capability to respond to customer requests for cost estimates. He ensures the division cost proposals are complete, accurate, and minimize cost risk. He serves as a key interface with the functional line departments, program office, senior management, auditors, and customers. Finally, he must review and approve all formal cost and price proposals for content and conformance with government regulations, public law, and customer requirements.

The cost proposal cycle for Litton Applied Technology consists of thirteen distinct steps. The individual steps, in successive order, are:

1. Receipt and acceptance of the customer's request for proposal.
2. Assign a proposal team manager.
3. Issue the proposal authorization to proceed order.
4. Assemble the proposal team, with representatives from Engineering, Quality Assurance, Operations, Contract Administration, and Proposal Cost Estimating and Analysis.
5. Conduct proposal team planning meetings. The team must establish a tentative program schedule and develop the work breakdown structure. The bid matrix, which designates the individuals responsible for the cost estimate for every single element, is promulgated.
6. Brief senior management of the team's plans at a

one-hour kickoff meeting.

7. Review the proposal strategy and technical approach at previously defined intervals.
8. Identify all material requirements.
9. Collect and analyze the cost estimates.
10. Conduct final management review.
11. Prepare the proposal submittal volume.
12. Submit the proposal to the customer.
13. Complete audits and negotiations by the customer.

The key member in this matrix concept for cost estimating is the proposal analyst assigned from the Proposal Cost Estimating and Analysis Division. He is responsible for the compilation and analysis of the estimated costs submitted by the personnel designated in the bid-matrix structure. Also, he performs "make-or-buy-analysis" on selected high dollar value parts.

The general cost estimating approach by the proposal team is the "bottoms-up" cost engineering method. The bottoms-up method is utilized for every proposal, from development of new designs to full-scale production cost proposals. The key steps the team performs for cost analysis are:

1. For existing design configurations, the proposal analyst retrieves a computerized bill of material from the on-line material pricing system.
2. For new designs, the responsible functional organization will generate a bill of material and send it to the proposal analyst.
3. The proposal analyst develops a priced bill of material with support from the Procurement Material Pricing Department for inclusion in the cost proposal.
4. The functional organizations submit their direct and indirect labor estimates to the proposal manager for review.

5. All functional cost estimates are given to the proposal analyst to create the preliminary cost roll-up.
6. Preliminary cost reviews with senior management are conducted.
7. The proposal analyst receives the cost review results. He next compares them with the cost history on similar programs for reasonableness.
8. All team members review the revised cost estimates to ensure they are factual, verifiable, complete, and support the proposed amounts.
9. The proposal manager and proposal analyst brief the company executives at the Final Management View to defend their cost estimates.

For every stage in the cost proposal development process, checkoff sheets are generated. Signatures by the responsible individuals are obtained to indicate completion for every step. The proposal analyst primarily verifies the functional groups' cost estimates for labor hours and material quantity. On production contract proposals with little risk, the proposal analyst generates the cost estimate himself based strictly on historical data. Company officials estimate that an average of three complete cost estimate reviews are conducted before final approval.

E. COST ESTIMATION METHODOLOGY FOR DERIVATION OF DIRECT COSTS

Litton Applied Technology's Cost Estimation and Pricing Manual defines direct material as the cost of material used in making a product which is directly associated with a change in the product. Litton's direct material base is comprised of raw materials, purchased parts, and subcontracted items. For raw materials, a raw stock factor is applied to the total estimated material base to account for these costs. In their system raw materials which require further processing are treated as indirect costs.

When budgetary estimates, also called ROM (rough order of magnitude) estimates, are requested for supplied of existing products, they are based on the most recent firm estimates of the same or similar items. The prior estimate is adjusted by the analyst for quantity differences and the degree of complexity. An annual escalation factor is added to the prior material estimate to account for period of performance differences. The difference in quantity is adjusted by utilization of a ninety-five percent improvement curve. The proposal manager, assisted by the functional engineering team members, provide the complexity factor for material estimates to the cost analyst.

Follow-on spare parts estimating is based on Litton Applied Technology's on-line computerized material pricing system. The source data for the computerized system represents the most current configuration for released part lists. Proposal analysts have the capability to extract the purchase order history of selected spare parts dating back to 1975. The analysts incorporate this information to the priced bill of material. The computerized on-line system can generate a priced bill of material by either the individual assembly or part number, or a consolidated group of part numbers. The computer's primary files from which the bills of material are generated are the engineering configuration file and the manufacturing configuration file.

The Proposal Material Audit Report is Litton's name for the computer generated list of material prices based on the purchase order history. Litton's policy for high dollar value/high usage parts dictates a preference for current vendor quotes instead of sole reliance on previous history. Their normal procedures mandate at least three competitive quotes must be obtained. Follow-on spare parts are also adjusted in quantity by Litton's ninety-five percent improvement curve. Escalation factors for the period of performance differences also are included.

If there is no previous history of a material purchase, the proposal analyst requests via a standard material pricing request form that the Purchasing Material Pricing Department obtain vendor quotes. The functional proposal team members provide the physical description to the proposal analyst.

Estimates of material requirements for the SOA development projects, such as the conceptual exploration phase of the AN/ALR-67 Radar Warning System, are based on the "bottoms-up" system engineering approach. The cognizant engineer at the lowest level of the work breakdown structure develops the bill of materials after detailed analysis of the proposed design configuration specifications. The responsible engineer provides the quantity, part number, and description of the required materials in accordance with the bid task matrix instructions. The required bill of material is passed to the proposal analyst via the Material Cost Estimate Detail Form.

The material requirements for new developments are based on:

1. Similarity to existing equipment.
2. Vendor catalog items.

The priced bill of material based on "similar to" equipment is adjusted by a qualitative complex factor. For items never previously purchased, the complexity factor is determined by a consensus among members of the proposal team.

Once the dollar estimates for the material estimates are gathered, the proposal analyst next develops the Principle Items List. This list will include a previously determined numerical sampling of high dollar/high usage items. The written rationale for each item must include:

1. Part number.
2. Known or anticipated source.
3. Total quantity.
4. Unit and total price.
5. Competition status.
6. Basis for establishing the source.
7. Determination for reasonableness of cost.

The proposal analyst justifies cost reasonableness for the selected items based on inputs from the Procurement Material Pricing Department. The proposal analyst next presents the list for approval to the proposal and business area managers during formal cost input coordination meetings.

The Direct Labor Narrative Statement is another document required for the cost estimate of the proposal. Upon completion, both the functional proposal team representative and the cognizant functional director are required to sign it. The document should show enough detail to separate labor for each distinct operation. Each operation is identified by an engineering cost center and labor category. The estimates for direct labor costs must consider whether prior relatable efforts exist or if no verifiable labor cost data can be found. The estimates are performed at the lowest level of the work breakdown structure.

For prior relatable efforts, the copy of the previous cost report is attached if the estimated hours bid are identical or directly related in terms of equivalent technical complexity. The proposal cost analyst will review the incurred labor hour costs on sample task work orders to audit the validity and accuracy of the prior related task.

The proposal analyst must search for more detailed evidence if the prior relatable effort is of varying complexity to the present effort. The labor hours currently estimated are compared directly to a similar effort for which verification of incurred hours exist. The proposal analyst compares the present effort to the prior related task by developing a ratio based on the relative technical complexities of the two tasks. The percentage difference must be explained by identifiable documentary evidence such as the following:

1. Differences in number of units to be assembled.
2. Variance in assembly component count.
3. Differences in number and type of cables.
4. Differences in testing requirements.
5. Comparison of technical and performance differences.
6. Size or weight differences.

To achieve consistency on the Direct Labor Narrative Report, the prior effort is assigned a complexity base value of one. The narrative portion should specifically cite specification paragraphs which account for the difference in the plus or minus technical requirement.

If no background verifiable data can be found, the narrative should explain how the direct labor costs are derived. Sources such as conceptual estimating guides should be indicated by title; for example, "Electronic Cost Estimating Data", by Fred Hartmeyer. The basis for level of effort proposal estimating should also be stated. The reasons or rationale for labor cost estimates which are purely judgmental is also documented by the proposal analyst.

The cost accounting system for Litton, incorporated in the computerized on-line system, provides historical data at the work order level, task level, and project level by expense center code, for direct labor costs. An annual labor escalation factor consistent with that utilized in direct labor rate projections is applied to estimates based on prior related efforts.

The historical data utilized for direct labor estimating includes the following:

1. Direct Labor Hour Audit Report: shows manufacturing work order closures for the latest two years by assembly number. A ratio for unit average hours by expense center code for each part number is derived by summation of the manufacturing work order closure hours.
2. Proposal Direct Hours Report: shows two years of labor hours data for all subassemblies in the requested assembly. This report is utilized for manufacturing related tasks.
3. Material Work Order History Cost Estimating Summary Report: summarizes total unit hours by expense center code for the requested assembly which Litton will locally manufacture.
4. Contract Cost Status Report: provides, for non-manufacturing tasks, the historical data base for similar tasks.

Litton Applied Technology's methodology for direct labor estimates for development programs is similar to the process described earlier for all labor hours estimates. The only added feature for development program estimates is an increased emphasis on documentation via narrative analysis for complexity adjustments. The proposal analyst applies appropriate direct labor hour bid rates. The proposed bid rates are determined by examining the period of performance of the program plan and arriving at the midpoint of the effort. Historical bid rates are determined by dividing the quarterly total dollars expended by the quarterly total labor hours incurred for each expense center code.

The other direct costs included in every Litton development or production program estimate are:

1. Vendor Nonrecurring and Tooling: These represent the vendor costs associated with development, start-up, and tooling costs to produce and deliver equipment. The basis for this estimate consists of written vendor quotations or historical data such as prior purchase orders or project cost reports
2. Travel: Travel estimates consist of transportation and subsistence costs directly associated with the program estimate.
3. Field Service Differential: These costs include additional compensation over and above base salary expenses and per diem, which serve as an incentive to field support personnel on assignment.
4. Service Centers: The three service centers are Reprographic Services, Programming Services, and Word Processing Services. The cost estimates use hourly billing rates based on forecasted utilization and operational costs for the service center. The costs are estimated either by prior verifiable experience or the estimated number of hours the service will take.

Litton Applied Technology also uses estimates of direct labor hours in their derivation of indirect pool costs. The six indirect pools are:

1. Material overhead: This rate is determined by the ratio of annual total indirect costs for each expense center code divided by the total dollar value of the material base, including scrap and raw stock.
2. Fringe benefits: This rate is calculated by the ratio of annual fringe benefit expense costs divided by the total division labor dollars expended.
3. Sunnyvale plant overhead and Georgia operations overhead: Both pool rates are based on total plant overhead dollars expended annually divided by total division direct labor dollars plus their associated fringe benefit costs.
4. Field service overhead: This rate is based on total annual overhead costs divided by direct labor costs.
5. General and administrative expenses: These expenses consist of independent research and development, bid and proposal cost estimating, executive staff, general accounting, resource allocation and control, and defense systems business development costs. The rate is based on total expenses divided by the forecasted total costs sum allocable to contracts.

Besides the indirect rates, direct factors such as manufacturing overtime premium, material raw stock, and manufacturing and engineering support services are also allocated. Engineering support functions include software engineering and development, and engineering design support. Manufacturing support services include operations control, shipping, and the test directorate staff. The rate for these functions is based on the ratio of the six month historical average of direct labor hours for each service.

F. ACTUAL COSTS FOR THE AN/ALR-67 RADAR WARNING RECEIVER

Litton Applied Technology received its first contract in 1975 under a cost plus fixed fee basis from COMNAVAIRSYSCOM, Washington, D.C., to develop the AN/ALR-67 Radar Warning Receiver. Due to budget constraints at the Navy level, this initial concept exploration contract was cancelled three times between 1975 and 1979. During the interim periods Litton Applied Technology utilized their own funds to continue the development with a skeleton force of five to ten people. Litton estimates they spent $400,000 of their own funds during 1976 on the AN/ALR-67 development, with the hope of being reimbursed. The initial contract amount was for $680,000. Contract modifications increased this amount to $1,000,000 before funds were temporarily shut down in 1976. Subsequent modifications, eventually totalling 100 altogether, increased the final development cost total to $6,530,000 under the contracted amount. Litton Applied Technology actually spent $10,541,541, incurring a $4,000,000 cost overrun. Ninety-four percent of the development effort occurred between 1975 and 1978, with the remainder of the effort continuing through 1980. A total of seven prototype models were built between 1975 and 1980.

The next contract covered the time frame from October 1982 to December 1985. This contract called for limited production of 43 ALR-67 systems. For this production start-up endeavor a fixed price incentive type contract was negotiated, placing more of the cost risk on Litton Applied Technology. The ceiling price on this contract wa $46,600,000 for the 43 systems.

Since 1985, a full scale production contract has been awarded by the Navy for 200 additional systems at a total price of $103,000,000. This contract is still ongoing.

Table 4 presents a budget and actual expenditure summary for contract N00019-75-C-0390. The actual development costs were broken into:

Software design	$ 1,300,000
Hardware design	$ 5,100,000
Hardware fabrication	$ 2,200,000
Data	$ 1,100,000
Test requirements	$ 800,000
TOTAL	$10,500,000

The actual costs for the limited production contract were:

Productionizing	$11,400,000
Tooling and tests	$ 5,400,000
Data	$ 3,000,000
Hardware	$28,600,000
TOTAL	$48,400,000

G. PREVIEW OF NEXT CHAPTER

Chapter Five analyzes the cost data through a brief variance analysis of the listed cost elements. It also includes a summary of the findings from the case study interviews, as well as an examination of possible new directions and trends for cost estimation of SOA projects.

TABLE 4

AN/ALR-67

FUNDING AND EXPENDITURE SUMMARY

AUGUST 1987 (MONTH ENDING 8/28/87)

CLIN #	DESCRIPTION	FUNDED	EXPENDED TO DATE
SECTION E			
	DEVELOPMENT	$6,530,000	$10,541,541
	OPTION	$1,255,566	$ 1,332,510
SECTION F			
0002	PGSE	$3,514,134	$ 3,563,040
0003	SPARES/HARM	$1,675,363	$ 1,711,661
0007	GSERDS	$ 332,054	$ 309,529
0024	ENG. SUPPORT	$1,749,008	$ 1,778,548
0025	TEST SUPPORT	$4,252,944	$ 4,233,552
0026	ENG. SERV/SYS S/W	$3,527,127	$ 3,733,792
0027	FIELD ENG. SUPT	$ 200,000	$ 194,326
0028	TEST SUPT (M-DEMO)	$1,546,770	$ 1,304,369
0029	ENG. SERV/SYS S/W	$2,340,000	$ 2,055,206
0030	F/A-18A INTGRTN	$ 146,607	$ 148,464
0031	F/A-18A I/F	$ 520,550	$ 471,000
	TOTAL	$27,640,773	$31,427,760

V. CASE ANALYSIS AND FUTURE TRENDS

A. INTRODUCTION

This chapter provides an analysis of the cost estimating methodology used by Litton Applied Technology. Emerging trends in measuring and controlling SOA costs for the future are discussed. Specifically, this chapter provides the following:

1. A variance analysis of the AN/ALR-67 Radar Warning Receiver development program.
2. An overall analysis of Litton Applied Technology's cost estimating system.
3. A discussion of current concerns and directions within the cost estimating field, based on case study.
4. Thoughts about the roles cost estimators must assume in the future.
5. Comparison of Litton's cost estimating process to the current direction of the cost estimating field.

B. VARIANCE ANALYSIS OF THE DEVELOPMENT PROGRAM OF THE AN/ALR-67 RADAR WARNING RECEIVER

The majority of cost overruns for the current life cycle of the AN/ALR-67 Radar Warning Receiver occurred in the conceptual exploration period between 1975 and 1980. Variance analysis of the development costs indicates a cost overrun of $4,011,541, or 61.4 percent. The second largest contributor to the total cost variance was engineering services and systems software support, which overran the funded amount by 5.8 percent, or $206,665. Schedule variances could not be calculated from the data provided, since the category for funded costs was not further subdivided into budgeted cost of work scheduled and budgeted cost of work performed.

From discussions with company officials [Ref. 27], the primary reasons for the cost variances in the development phase were:

1. The sporadic nature of government funding. During the years 1975-1979, the project was stopped three times by the Navy due to funding constraints. The miscellaneous work stoppage and startup costs associated with this type of uncertainty were not completely compensated for by the Navy.
2. Poor software cost estimating. The AN/ALR-67 was the first Litton Applied Technology system to incorporate extensive software technology. Several cost analysts stated the amount of labor hours estimated to write the lines of code for the software development programs were significantly underestimated. There were no analogous programs to refer to for cost history comparisons. Litton Applied Technology does not utilize any generic cost estimation model in software or hardware.
3. Inadequate definition of the work breakdown structure. During the years 1975-1980, the work breakdown structure was developed by painstaking manual methods, rather than use of the current on-line drafting capability. Litton engineers found it difficult during the initial development phase to segregate the AN/ALR-67 prototype models into clearly defined lower level elements. This lack of definition led to problems of underallocation of funds as actual costs began rolling in.

4. Inflation and its effects on material costs. The years 1975-1980 were periods of rapid price increase for many defense electronics materials. As delays due to work stoppage mounted in these initial years, original material estimates became outdated. As a result, material prices were notably higher when purchased at the point of usage.
5. Effect of experience. The various work stoppages during the development phase hindered the learning curve progression to an unmeasurable degree. As a result, more rework than originally planned occurred, especially in software development.
6. Numerous contract modifications. Litton budget analysts estimated that 300 modifications due to engineering change proposals were added to the AN/ALR-67 development. These modifications accounted for the funded increase to $6,500,000 from the original contract amount of $680,000. Most modifications involved increased integration of circuits to provide added performance within the same size constraints.
7. Schedule pressure. During 1978, considerable pressure was exerted by the Navy to accelerate fabrication of the engineering development models. This pressure led to an unplanned increase in the number of workers and an increase in rework, both of which contributed to cost increases.
8. Lack of formal controls. Litton Applied Technology did not have a well-documented control system of checklists and unplanned audits in the period 1975-1980. Internal investigations of

variance were not available for review for contracts during this period. This era also predated the DOD procurement reform measures of the mid-1980's, which required more stringent control systems by government contractors.

C. OVERALL ANALYSIS OF LITTON APPLIED TECHNOLOGY'S COST ESTIMATING SYSTEM

This analysis of the cost estimating system for the AN/ALR-67 Radar Warning Receiver and Litton Applied Technology is based on the six managerial subsystem characteristics of the Katz and Rosenzweig Model, which are environmental, technical, goals and values, psychological, managerial, and structural. [Ref. 27]

1. Environmental

The environment which influences Litton Applied Technology is much different in 1987 than it was during 1980, the end of the development period. In 1980, Applied Technology was still a separate company from Litton, so it could not depend on large corporate resources for assistance. Applied Technology encountered erratic government funding for its first major weapons system to use software extensively. Also, competition from other defense electronics companies was not as intense in 1980 as in 1987. For example, the concepts of contractor teaming, dual sourcing, and leader-follower for development projects were not introduced to the defense industry until several years after the conceptual exploration phase for the AN/ALR-67 was completed. These external environmental factors which differentiate the period 1975-1980 from 1987 allow insight into how Applied Technology has evolved to meet the current defense climate via structural and technical changes. Defense contractors, in 1987, face more intense scrutiny on cost performance than they encountered in 1980 for development contracts.

2. Technical

Litton Applied Technology has greatly improved its cost estimating capabilities. They currently use a new IBM mainframe computer system to keep track of price histories, work breakdown structures, and vendor quotes. However, they have made a conscious decision not to utilize generic parametric cost estimating models which could be adapted to the mainframe system. Litton cost analysts believe the physical dimensions of their radar warning receivers are too small for accurate application of the RCA Price cost estimating model, for example. As a result, all cost improvements are geared toward upgrading their bottoms-up cost estimating capability. Their emphasis is on cost performance trend analysis for their own products.

Litton Applied Technology's cost estimators understand the difficulties of accurate estimation for the new integrated circuits of the future. The SOA for Litton's radar warning receivers will extend into increasing miniaturization of components, which will be more reliable and capable than their predecessors. Litton estimators currently expect vendor-purchased electronic components to decrease in price in the next few years due to better integrated circuit technology and yield improvement. Litton will continue to rely on its mainframe cost collection system and group judgment techniques to estimate costs for SOA extensions, with no foreseeable plans to incorporate regression analysis or cost prediction models. Finally, due to its mainframe capabilities, Litton rarely uses personal computers in its cost estimation process.

3. Structure

Structurally, Litton Applied Technology utilizes a matrix organization concept for its cost estimation process. With this system they draft members from functional departments to participate in the cost proposal process, terminating the team upon completion of the negotiated contract.

Litton Applied Technology has the functional department heads review and approve the proposal team's recommendations. This current system does not allow any one individual the opportunity to wield an overwhelming influence on cost estimates. The situation differed slightly from 1975-1980, when the AN/ALR-67 program management team remained intact and exerted considerable independence.

4. Psychosocial

At the psychosocial level, Litton Applied Technology has made tremendous strides for its employees. At its south San Jose location, a new building with plush offices, a complete cafeteria, and recreational facilities have been added to improve company morale. Litton requires all employees, including executives, to refer to each other by first names only. Litton's executives also meet annually at special retreats to discuss the current state of the company and its future strategy.

Most of Litton's cost estimators are relatively young, with an accounting background from college. Litton trains these estimators themselves, rather than relying on outside cost estimating seminars. They do not participate in the Space Systems Cost Analysis Group or belong to the International Society of Parametric Analysts. Litton has recently published a comprehensive "Pricing and Estimation Manual" for its cost analysts. However, in 1980, few written guidelines were available for use by the cost analysts.

5. Managerial

The managerial process at Litton Applied Technology is heavily weighted toward planning and organization. Almost every area of the building carries its own blackboard and space for meeting rooms. According to the Pricing and Estimation Manual, most meetings have set time limits of five to ten minutes per topic. Litton exhibits a strong vertical decision-making structure, since functional department levels usually do not deal with other functional lower levels unless prior liaison has been arranged by the department heads.

6. Goals and Values

Litton Applied Technology's goals and values emphasize quality workmanship and reliability. Their marketing personnel's primary emphasis is on the excellent performance and versatility of the radar warning receivers in combat situations. At proposal team meetings, the actual cost estimates are usually not the primary issue. Proposal meeting agendas concentrate on analysis of the competition and packaging and presentation of the proposal itself.

7. Control Mechanisms

The AN/ALR-67's costs are currently controlled primarily through vendor control and monitoring of labor hours. Litton Applied Technology has established a vendor qualification program to meet its raw material needs, in order to minimize material defects. Vendor costs are controlled by trend comparison with prior related efforts on the mainframe history files. Litton Applied Technology's internal auditors monitor, via surprise visits, the recording of labor hours by each cost element.

In this researcher's opinion, Litton Applied Technology could more effectively utilize postaudits as a control mechanism. Their cost analysts receive little feedback on proposal cost estimates which are rejected in favor of another contractor. Postaudit conferences with cost analysis can provide an effective "lessons learned" benefit for the future.

D. CURRENT CONCERNS AND TRENDS IN COST ESTIMATION

The current focus of practitioners of SOA cost estimating is on increasing the range and depth of the data base. During an interview with Dr. E.N. Dodson on 16 October 1987, he indicated a primary problem in cost estimating is the lack of good historical data to substantiate cost prediction models. Dodson indicated most data for cost models comes from after-the-fact analysis of costs at the production level. Dodson feels more rigorous analysis of costs at the design stage is critical for accounting for technological change. To properly understand the cost impact of new technology, Dodson stated cost estimators must become more knowledgeable in engineering. Engineering backgrounds would enable estimators to better locate the cost drivers which are influenced by technology parameters.

Another concern of modern cost estimators, according to Dr. Dodson, is the inability to influence potential costs during the initial phases of the design process. Dodson feels cost estimators should develop the capability to review performance parameters in the design process, and subsequently advise design engineers as to the legitimacy of the specifications.

For example, cost analysts should be capable of asking if less rigorous specifications could be substituted for more rigorous ones.

One shortcoming of many cost estimators, according to Dr. Dodson, is their failure to recognize old technology under the guise of new technology. Once estimators increase their technical knowledge, this mistake will be less likely to occur. Also, better subdivision of the work breakdown structure into definable cost elements should sort out old and new technology.

Dodson feels his theories on the use of surface fitting techniques and regression analysis to estimate SOA extension costs are too time-consuming and expensive. Most corporations involved in government cost proposals could not efficiently utilize these techniques. As Dodson indicates, DOD agencies prefer to audit detailed systems engineered estimates which substantiate every cost element. DOD agencies do not require parametric estimates of new developments, so cost estimators currently use cost estimation models only as a checking mechanism.

For SOA extension measurement, Dodson states his current focus is on transforming performance parameters to design parameters, and ultimately to cost. He emphasizes efficiency parameters should be utilized in selecting key technological variables. For example, he suggests receiver sensitivity, receiver bandwidth, and receiver frequency might be good indicators of SOA advance for radar systems.

Finally, Dr. Dodson states risk analysis of cost estimates is another area which requires further study. This area should quantify the probabilities that underruns or overruns will occur in development projects.

Stan Swales, the leading cost estimator for GTE Government Products and a member of the Space Systems Cost Analysis Group, also shared his opinion on the current trends of the cost estimating field. [Ref. 28] Mr. Swales recommends the use of Expert Systems, a branch of artificial intelligence that is concerned with emulating the problem solving processes of human experts. On 28 July 1987 he stated "Expert Systems is the wave of the future." He feels Expert Systems technology optimizes the exchange of information and improves the evaluation of data. For Mr. Swales' system, cost engineers interview experts and program their answers into the knowledge base of the Expert System. The knowledge base should eventually consist of rules, cost estimating relationships, and a numeric data base. The next phase of Swales' Expert System concerns the inference engine, which contains the control strategies and control structures for the model. The cost predictor portion of the model develops cost estimates for programs by combining the control given by the inference engine with the user's input data and the knowledge base. Although Swales utilizes this model to predict costs of programs [illegible] conceptual exploration stage, it has [illegible] completely implemented into GTE's form[illegible] estimating system. The current appl[illegible] Expert System does not specifical[illegible] extension costs.

Stan Swales states [illegible] estimating problems by [illegible] methods. He believes [illegible] algorithmic [illegible]

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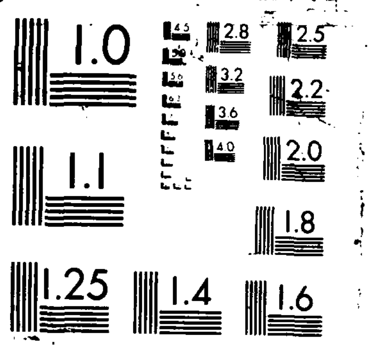
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judgmental cost estimating process than conventional methods can. In his presentation on Expert Systems to the Space Systems Cost Analysis Group on 24 September 1986, he drew three conclusions:

1. Expert Systems rapidly adapt to any type program, with benefits increasing exponentially with program complexity.
2. Expert Systems cost models designed for desk-top computers reduce proposal times and improve program cost control.
3. Expert Systems techniques reduce potential for program cost overruns.

E. EMERGING ROLES COST ESTIMATORS MUST ASSUME IN THE FUTURE

This researcher discovered through personal interviews with Dr. E.N. Dodson and Stan Swales that most leading cost estimators have also attained a broad engineering background. During a presentation to the International Society of Parametric Analysts during March 1987, Mr. Edward Laughlin discussed the role cost estimators must assume to properly assess future technologies. [Ref. 29]

Laughlin stated cost estimators must improve their understanding of the total implications of new technology. He believes analysts must develop closer coordination with the engineering community to better understand the technical implications of resource management decisions. They must be fluent in acquisition, budgetary, and technical languages since the cost analyst will become an integrator of staff information in the future. For example, Laughlin writes:

> We can't afford to look blank when people start talking about flexible manufacturing, fiber optics,

robotics, and composite materials because we're going to be tasked to recommend important and costly decisions that can't be made with yesterday's knowledge. [Ref. 30]

Laughlin believes cost estimators must have diversified experience and a broad based education to understand the cost impact of new technology. He recommends that data bases concentrate on accumulating information on technological cost drivers, rather than massive storage of cost histories. He also recommends that cost estimators continually update their education and training on future hardware and software trends, such as computer aided design (CAD) and artificial intelligence. Finally, Laughlin recommends engineering specialists become permanent members of cost analysis divisions to increase the interdependency between engineers and cost estimators.

F. COMPARISON OF LITTON'S COST ESTIMATING PROGRAM TO CURRENT DIRECTION OF THE ESTIMATING FIELD

Litton Applied Technology's cost estimating system has evolved into a bottoms-up system engineered procedure which makes extensive use of a deep data base of prior related costs. Their data base consists of price histories for parts which date back fifteen years. Extensive labor rate data for carefully defined job descriptions are also entered into the data base. Their ability to adapt to the future direction of the cost estimating field, and their capability to estimate the cost of SOA advances, are assessed in the following paragraphs.

1. <u>SOA Advance Measurements</u>

Litton does not specifically measure the cost of the SOA extension. Dodson's use of ellipsoid surfaces to define the SOA performance parameters has not been addressed by Litton Applied Technology. Other

SOA measurement techniques, such as Alexander's regression analysis of primary parameters, are also not utilized. Even for conceptual exploration phase projects, Litton relies on consistent application of its bottoms-up system. The proposal analyst and the functional engineers use analogy methods when exact data from the WBS elements is not available. Litton cost estimators do not use generic parametric cost models such as PRICE or FAST.

This researcher feels Litton's expensive commitment to their bottoms-up method for SOA extension projects does not provide their analysts sufficient flexibility for "what-if" analysis. Their exploration of different alternatives is limited, since detailed documentation efforts at the WBS lower levels are mandated for each acquisition phase. Their exclusive use of the bottoms-up method does not provide information on the expense involved in increasing SOA parameters, such as receiver sensitivity, in a timely manner.

2. Expert Systems

Artificial intelligence applications to cost estimating will become more prevalent in the future. Litton Applied Technology, with its extensive cost data base, is missing an opportunity to improve its estimating capability by not investigating the benefits of this field. They already possess extensive computer capabilities which, coupled with their knowledge of radar warning receivers, makes them ideal candidates for expert systems.

Some of the opportunities the use of expert systems would present to Litton are listed.

a. Learning Tool

Expert systems give users the capability to obtain the experts' consensus judgment on what costs should be, based on the users' answers to system queries. Litton's cost analysts do not have postgraduate education or extensive engineering backgrounds, but implementation of an expert system would rapidly increase their capabilities to mimic an expert's answer.

b. Warehouse for Cost Estimating Knowledge

The expert system's knowledge data base would incorporate the expertise of Litton's most capable professionals. Their proposal analysis teams would gain consistency through use of the expert system, since recommendations by the system would be based on the same heuristic rules input to the system.

c. Pre-planning Tool

Expert systems, normally designed for personal computers, provide the rapid flexibility of what-if analysis missing in Litton Applied Technology's current system.

d. Research Tool

Litton's cost estimators could perform research on new projects by studying the implications of different parameters in a quick, iterative fashion.

Expert systems are expensive, and most are still in formative stages. This researcher recommends Litton track the progress of artificial intelligence in the cost estimating field. Cost benefit analysis should be performed to see if their data based management system would be significantly improved.

3. <u>Influence of Costs in the Design Stage</u>

Cost estimators at Litton do not yet impact planning of performance parameters at the design stage.

In the proposal cycle the cost analyst collects inputs from the WBS elements, after the specifications are already decided. However, with the rapid pace of technology, Litton will gain more effective control of costs through more rigorous analysis of costs earlier in the design stage.

4. <u>Understanding of Total Implications of New Technology</u>

Most Litton cost analysts have accounting backgrounds. They do not regularly attend professional cost estimating seminars. For Litton to improve its ability to estimate SOA extension costs, the estimators must understand how new technology will influence costs. The cost analysts should receive training on fields such as artificial intelligence and computer aided design. This researcher recommends high technology firms like Litton should consider inclusion of engineers knowledgeable in future hardware trends in the cost estimating division.

5. <u>Isolation of Cost Drivers</u>

Litton's ability to estimate SOA extension costs and control development costs would be enhanced by a thorough analysis of which design and performance parameters generate the most significant influence on cost. Isolation of the key cost drivers for radar warning receivers would enable planners to concentrate on cost reductions in these areas.

F. SUMMARY

This chapter's primary goal has been to analyze key features of Litton Applied Technology through specific study of the AN/ALR-67's development program. Preceding sections provided insight into the direction of the cost estimating field, and the qualities cost analysts must develop in the future, before reliable cost estimates for SOA extensions can be made.

The next chapter provides the final summary and recommendations for future study.

VI. SUMMARY AND CONCLUSIONS

A. INTRODUCTION

This chapter presents the summary and conclusions for this thesis. The primary focus of the research has been to determine how defense industry cost estimators measure the costs of SOA extensions for new weapons systems. The researcher utilized a case study of Litton Applied Technology's development of the AN/ALR-67 Radar Warning Receiver to present an actual example.

The literature review section highlighted the work of Dr. E.N. Dodson of General Research Corporation, a pioneer in the field of SOA measurement. Cost prediction models by selected authors were also examined to demonstrate how cost estimation theory is transformed to actual data. The last chapter highlighted current concerns and future trends in the cost estimating field.

B. LITERATURE REVIEW

The literature review section began with Ostwald's definition of cost estimating relationships as functional models that mathematically describe the costs of components as functions of one or more independent variables. Ostwald also described the roles cost estimators play in technological forecasting and development of cost indices.

Dr. E.N. Dodson has established himself as one of the foremost practitioners of quantitative measurement of SOA advances. He described the SOA for a particular system as an n-dimensional function at a particular point in time, with n representing the number of SOA design characteristics. He indicated geometric surfaces could illustrate the tradeoff between design characteristics for SOA advances. Dodson specifically developed SOA equations for solid propellant missiles. He also constructed SOA indices by geometric measures of data characteristics on an ellipsoid surface.

Alexander and Nelson of Rand Corporation measured technological change through multiple regression analysis. Their studies indicated performance, rather than technical, parameters were better descriptors of SOA advance.

Hovanssian recommended electronic systems include customer acceptance parameters at the development stage, such as operator approval, life cycle cost, and amount of maintenance required per operating hour. Cooley developed the TRAM model, which could analyze the effects of budget reductions on SOA development projects.

Other studies of technological advance were conducted by Gordon and Munson, who used experts to choose the proper parameters for their SOA extension equations. Finally, Marino further refined the role of surface analysis in SOA measurements.

C. COST MODELS

Four different cost estimating models have been examined in earlier chapters. The two primary ingredients in their development were:

1. Derivation of the work breakdown structure.
2. Development of cost estimating relationships for each cost element.

The cost estimating relationships at the lowest level of the WBS were derived by a variety of methods for these models, from parametric analysis to analogy comparisons. The cost models all provided a hierarchy of estimating systems, depending on the data available to the analyst. In Dodson's models, he recommended regression equations should only be used as a last resort.

The FAST model utilizes technological characteristics such as energy outputs for its foundation. Among the products of the FAST model are projections of funding requirements for each stage of the development cycle.

D. LITTON'S COST ESTIMATION SYSTEM

Litton Applied Technology utilizes a detailed bottoms-up cost estimation approach for all electronics systems projects, including those at the early development stage. They do not use parametric cost estimation models; they rely on an elaborate component cost history data dating back to 1975stored on their IBM Mainframe computer. Their cost estimation process involves eliciting judgments from many personnel from different functions organized in a matrix team structure. The final cost estimate decision is arrived at only after a series of judgmental steps at different committee meetings.

Litton Applied Technology experienced a cost overrun of 61 percent for the development phase of the AN/ALR-67 Radar Warning Receiver. Some of the reasons explaining this cost growth were Litton Applied Technology's lack of familiarity with software cost estimation, numerous additions of modifications, intermittent work stoppages, and poor definition of manually drafted work breakdown structures. They did not use any specific techniques or parametric cost models to estimate the actual cost of the SOA extension.

E. CURRENT DIRECTIONS

Multiple regression analysis, trade off surface analysis, and factor analysis have been used by various practitioners to measure and estimate the actual costs of SOA extensions. Research has now focused on analysis of the efficiency characteristics of the primary parameters which most completely describe the technological advancement. Interviews with Dr. Dodson suggest the results of these SOA extension studies have not been integrated into the current cost estimation models.

Other cost estimators, like Stan Swales, predict artificial intelligence will be used more extensively in cost estimation models in the future. However, there are no indications Expert Systems methodology has specifically addressed the issue of SOA extension measurement in actual weapons systems applications.

F. FUTURE ROLES

The cost estimator of the future must assume the role of an integrator between engineering and cost analysis. With many electronic hardware costs actually decreasing exponentially due to technological innovation, cost estimators must continually update their knowledge on the latest technological innovations. Data bases should contain information on the cost, performance, and physical characteristics of the primary cost drivers which influence technological advancement.

DOD project offices can reduce overruns in SOA development programs by decreasing the amount of administrative and specification changes during the conceptual exploration stage. However, to facilitate this, government cost estimators must become involved early in the design process, and advise engineers as to the cost tradeoffs of specification changes.

G. CONCLUSIONS

The following conclusions can be drawn from this study:

1. The systems engineered cost estimating approach is relied upon by Litton Applied Technology for its cost estimation methodology.
2. Various methods, such as Dr. Dodson's regression analysis and surface fitting techniques, have succeeded in measuring the cost of SOA extensions. These methods have not been utilized in actual applications by industry or DOD in their cost estimating models.
3. The fundamental ingredient to parametric analysis of technological advancements is specification of the relationship between cost, performance, and physical characteristics of the primary cost drivers.
4. The development program cost estimate requires a detailed work breakdown structure in a bottoms-up method to prevent cost omissions. Errors in this area are a frequent cause of cost overruns.
5. Cost estimators must possess technical knowledge of the task being estimated if they are going to competently measure the costs of technological advancement.
6. The cost estimating field is dynamically increasing its knowledge in the area of parametric desk-top models and expert systems. These systems are useful for rapid analysis of different possibilities.

H. RECOMMENDATIONS FOR FUTURE STUDY

Future thesis efforts are needed to track the progress of the cost estimating profession in its endeavor to quantify the costs of SOA extensions. Also, future studies should review the feasibility of a large, universal data base for all electronics systems, from which defense contractors and DOD cost estimators could extract information. Pooled efforts might accelerate the progress in transforming technological advancement theory to actual practice.

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